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**Bidram**

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(54) **MOBILE WORK STATION FOR TRANSPORTING A PLURALITY OF ARTICLES**

(58) **Field of Classification Search**  
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See application file for complete search history.

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(57) **ABSTRACT**

**Related U.S. Application Data**

An apparatus and method for transporting a plurality of articles is disclosed. The apparatus includes a wheeled chassis, and a platform disposed on the wheeled chassis. The apparatus also includes a manipulator coupled to the wheeled chassis and operably configured to load a first article of the plurality of articles at a first position on the platform, or unload the first article of the plurality of articles from the first position on the platform. The apparatus further includes at least one actuator operably configured to cause successive relative rotational movements between the manipulator and the platform to provide access to successive rotationally spaced apart positions on the platform for loading or unloading each subsequent article in the plurality of articles.

(60) Provisional application No. 62/383,747, filed on Sep. 6, 2016.

(51) **Int. Cl.**

**G05D 1/02** (2020.01)

**B25J 19/02** (2006.01)

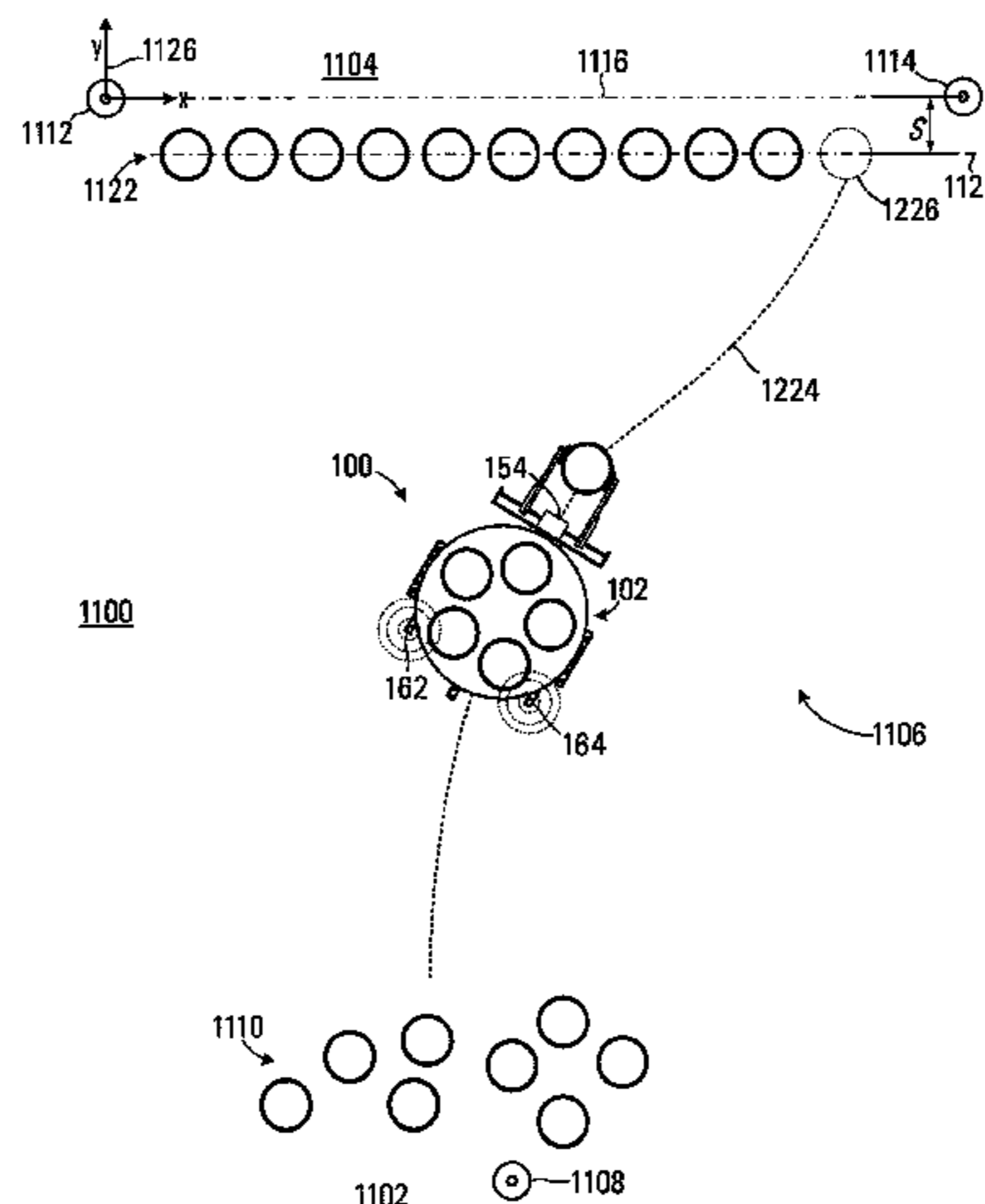
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**11 Claims, 13 Drawing Sheets**



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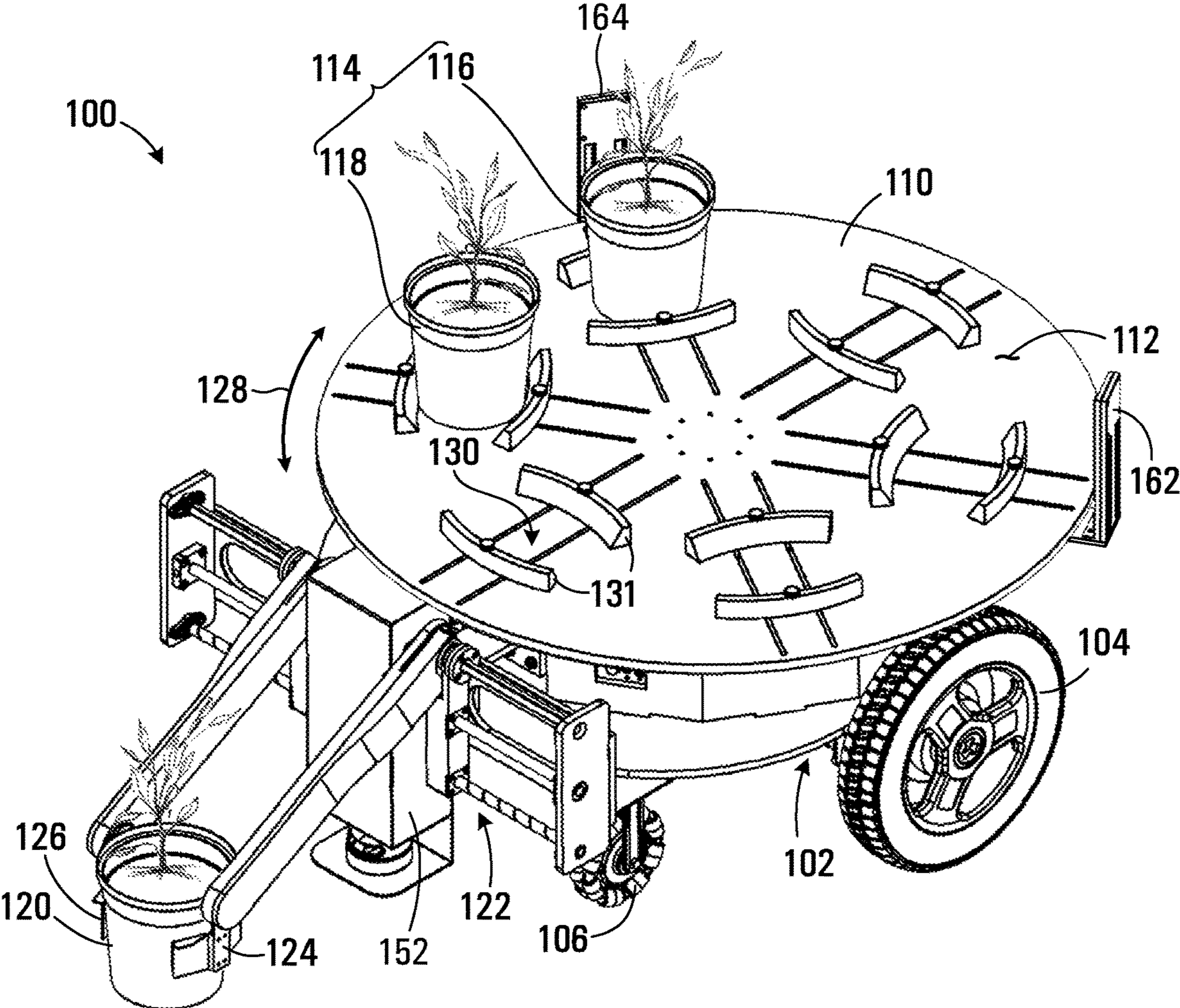


FIG. 1

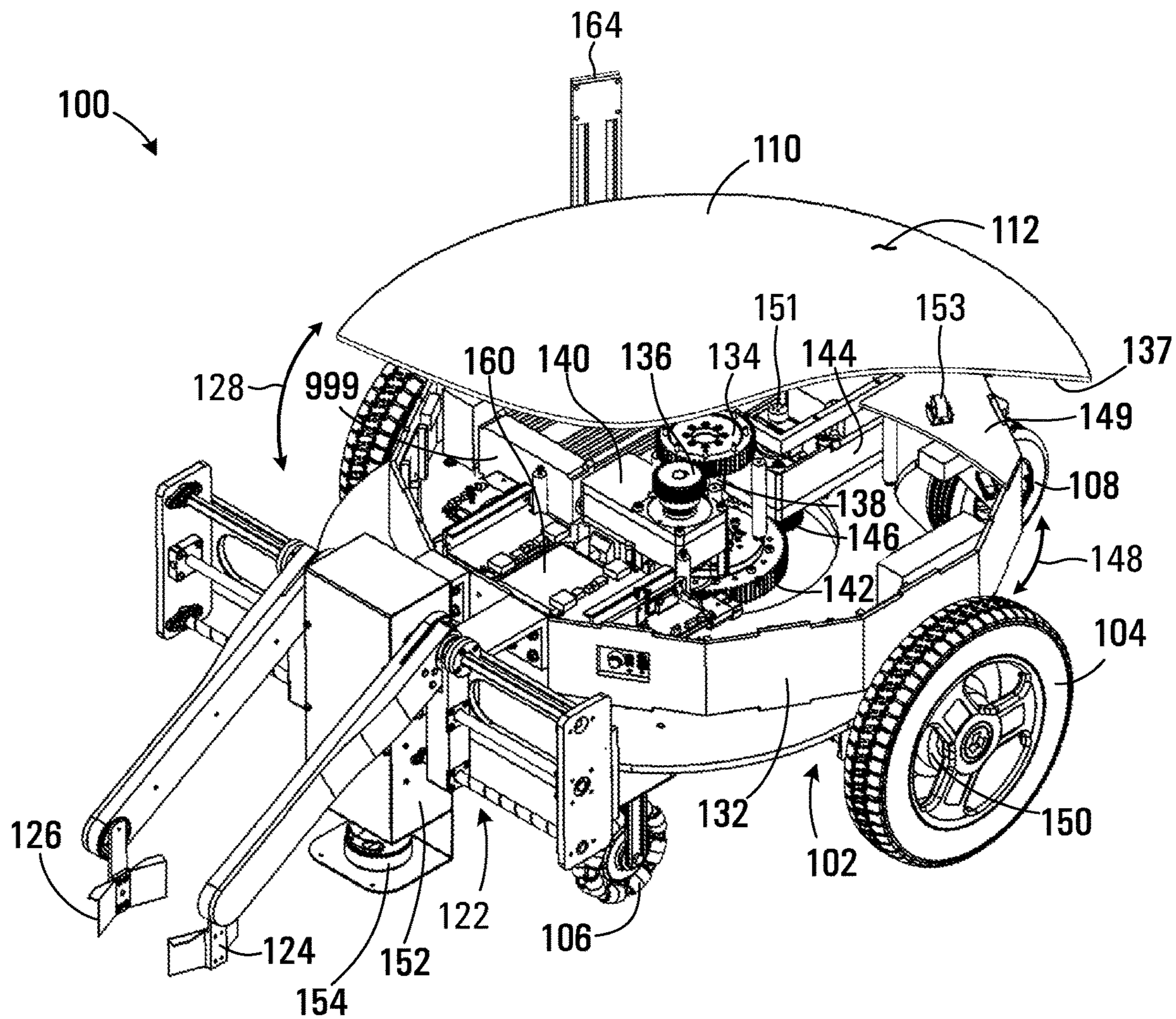


FIG. 2

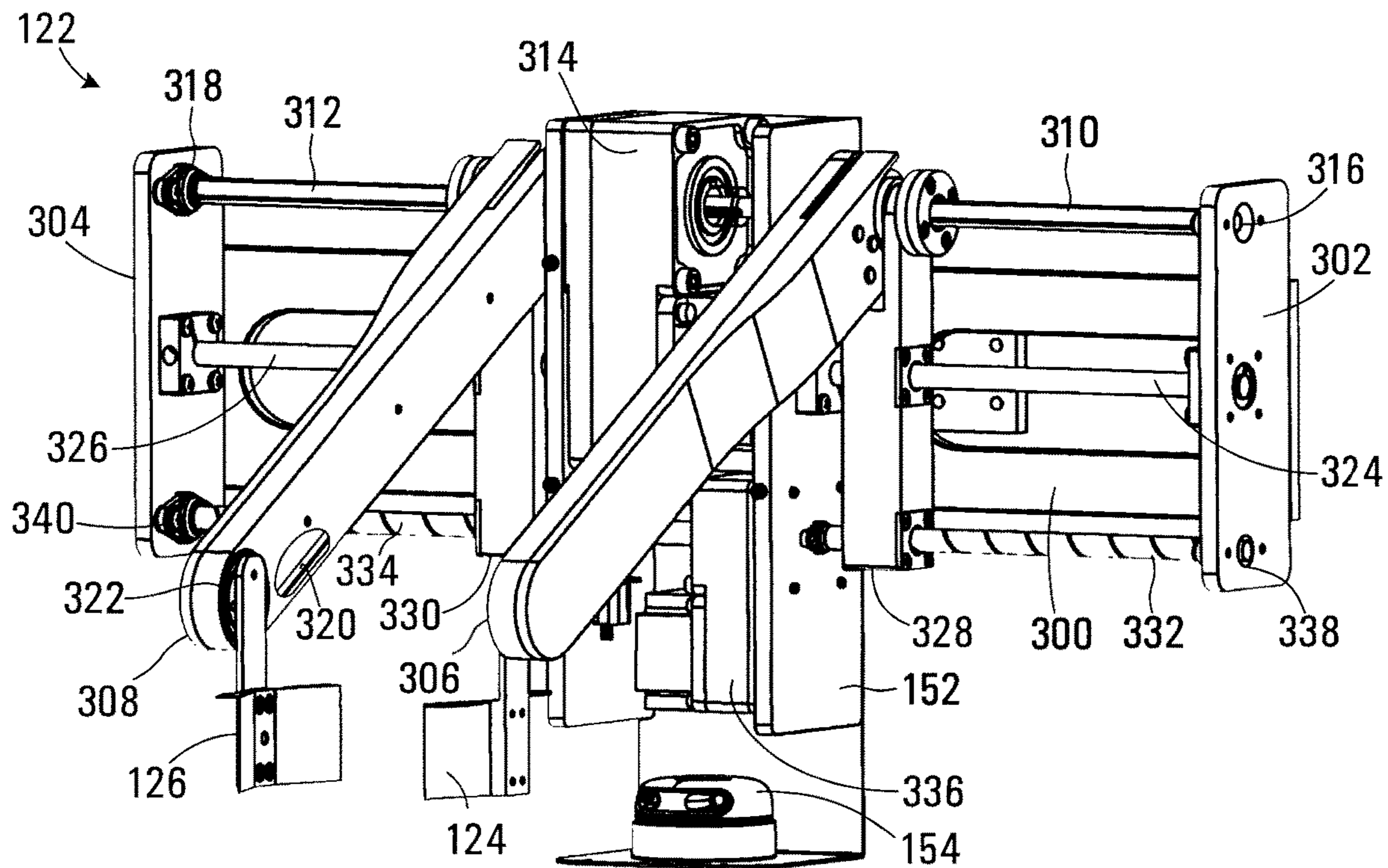


FIG. 3

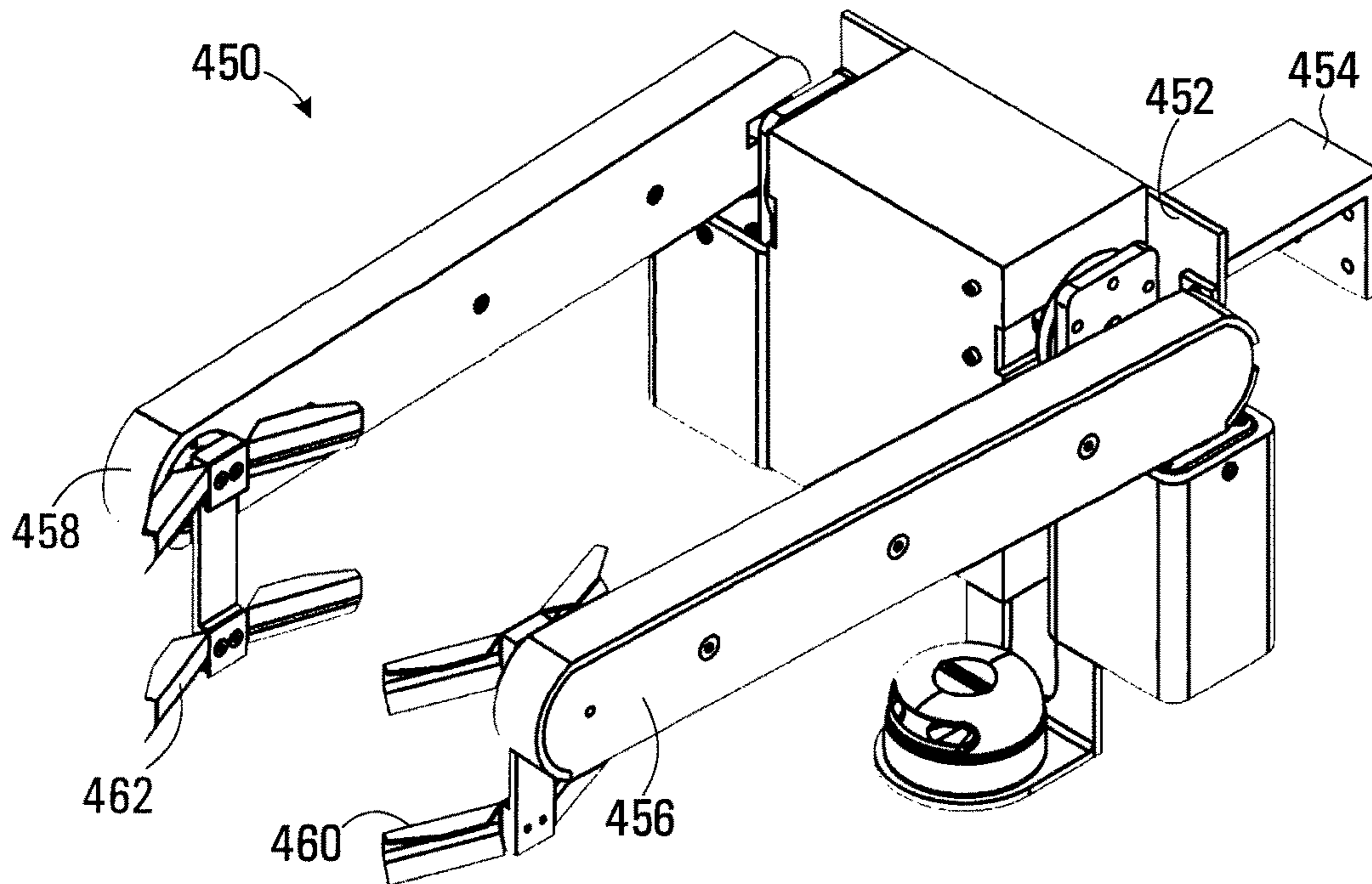


FIG. 4

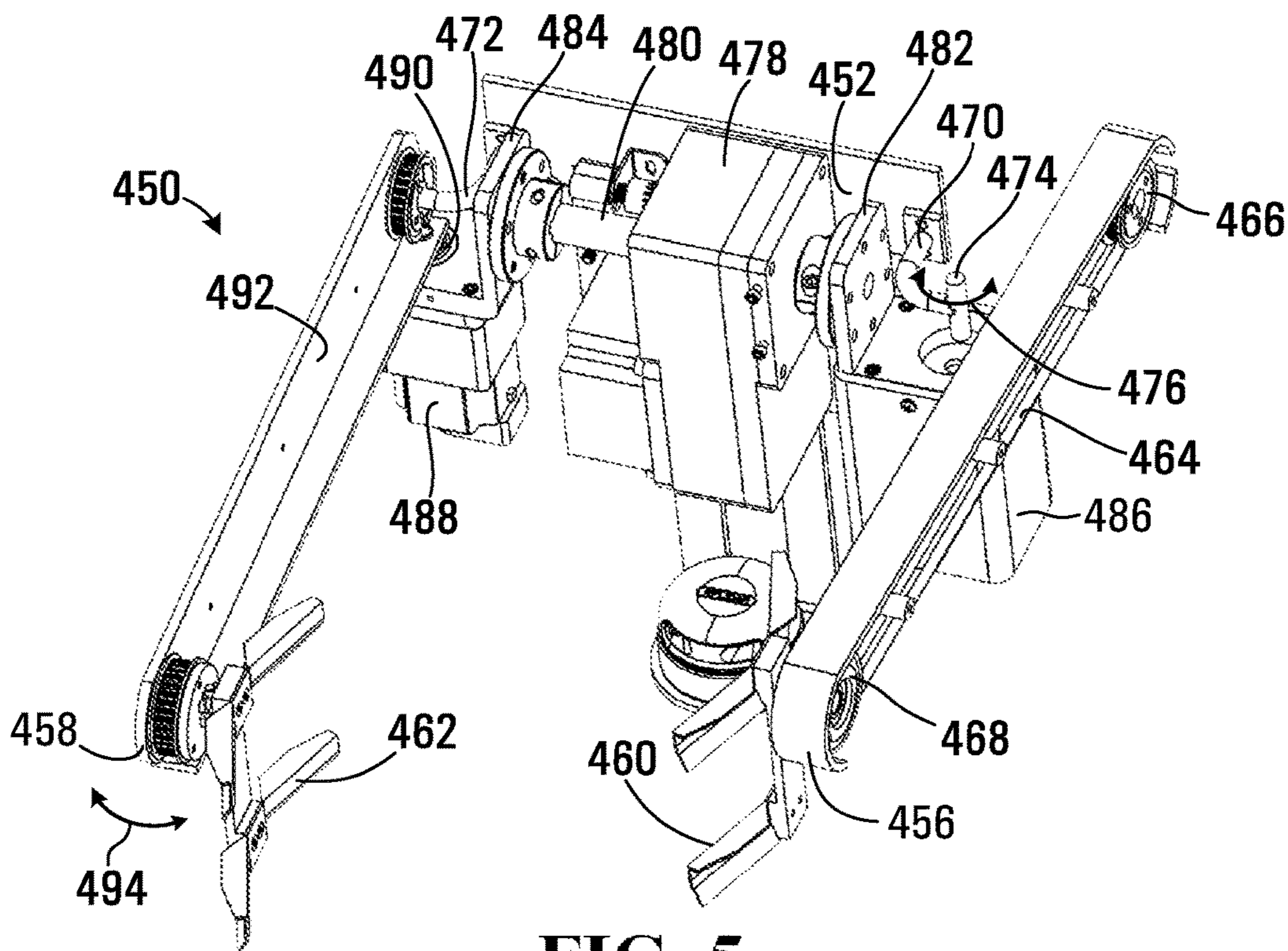


FIG. 5

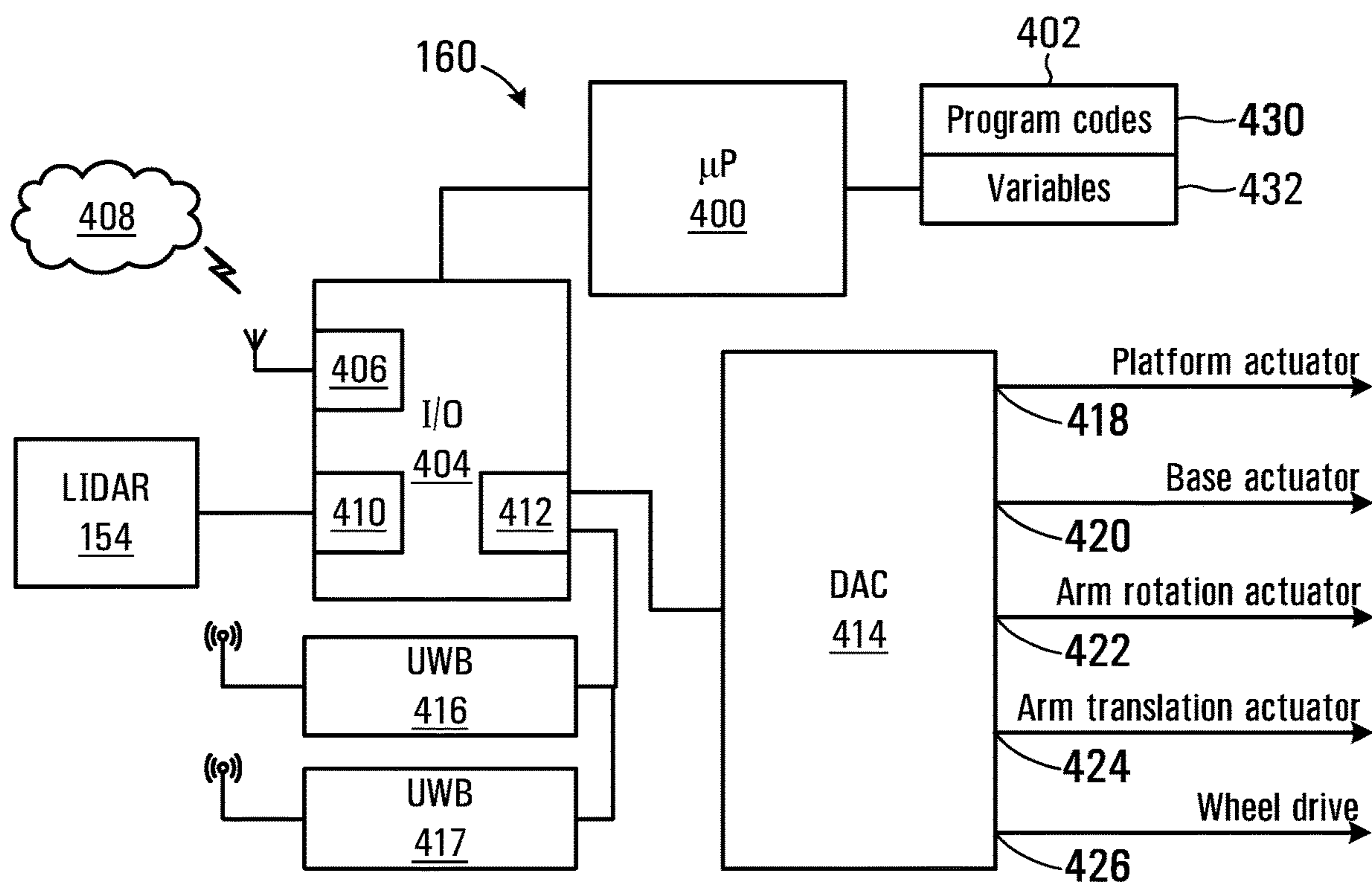


FIG. 6

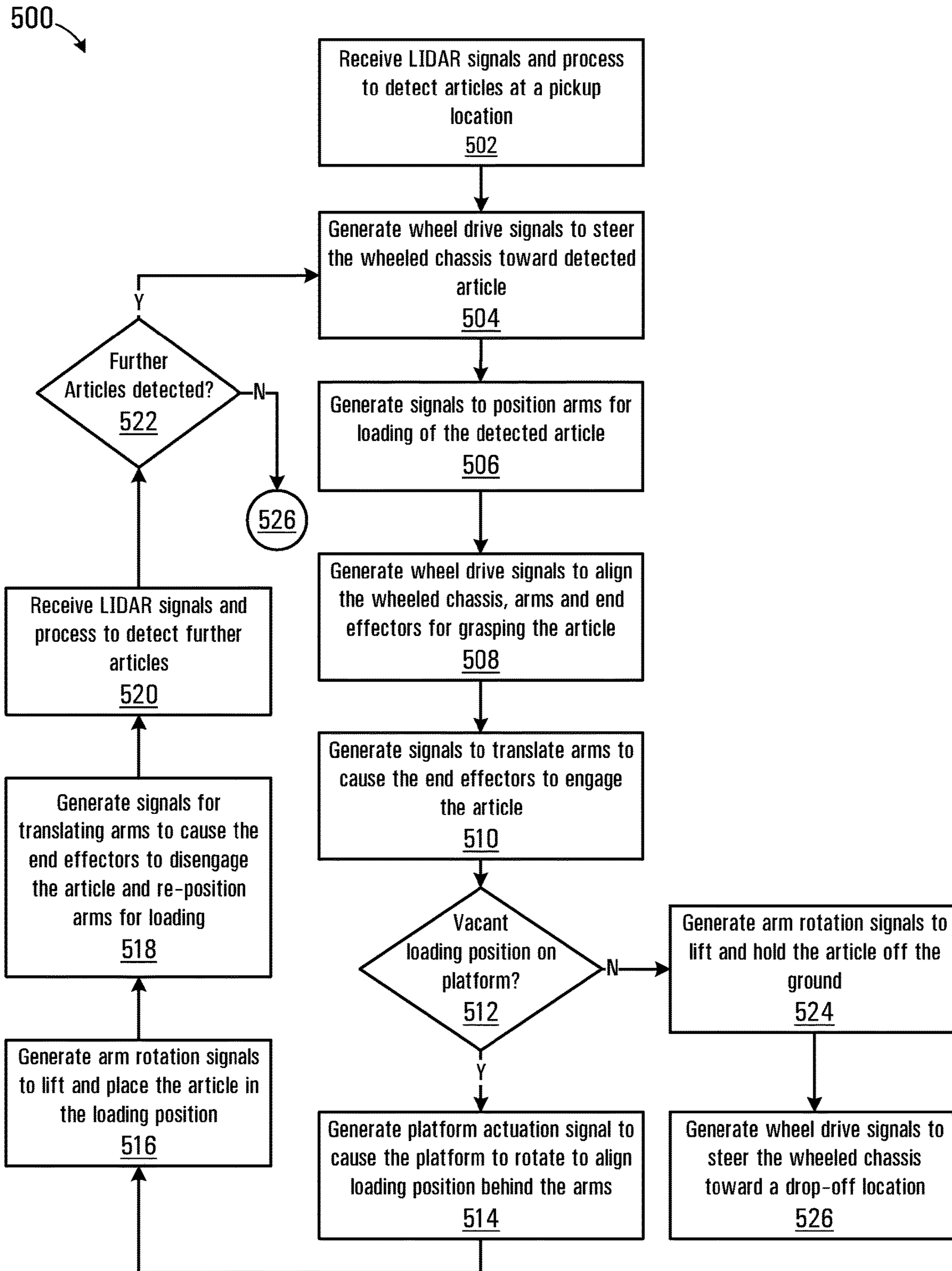


FIG. 7

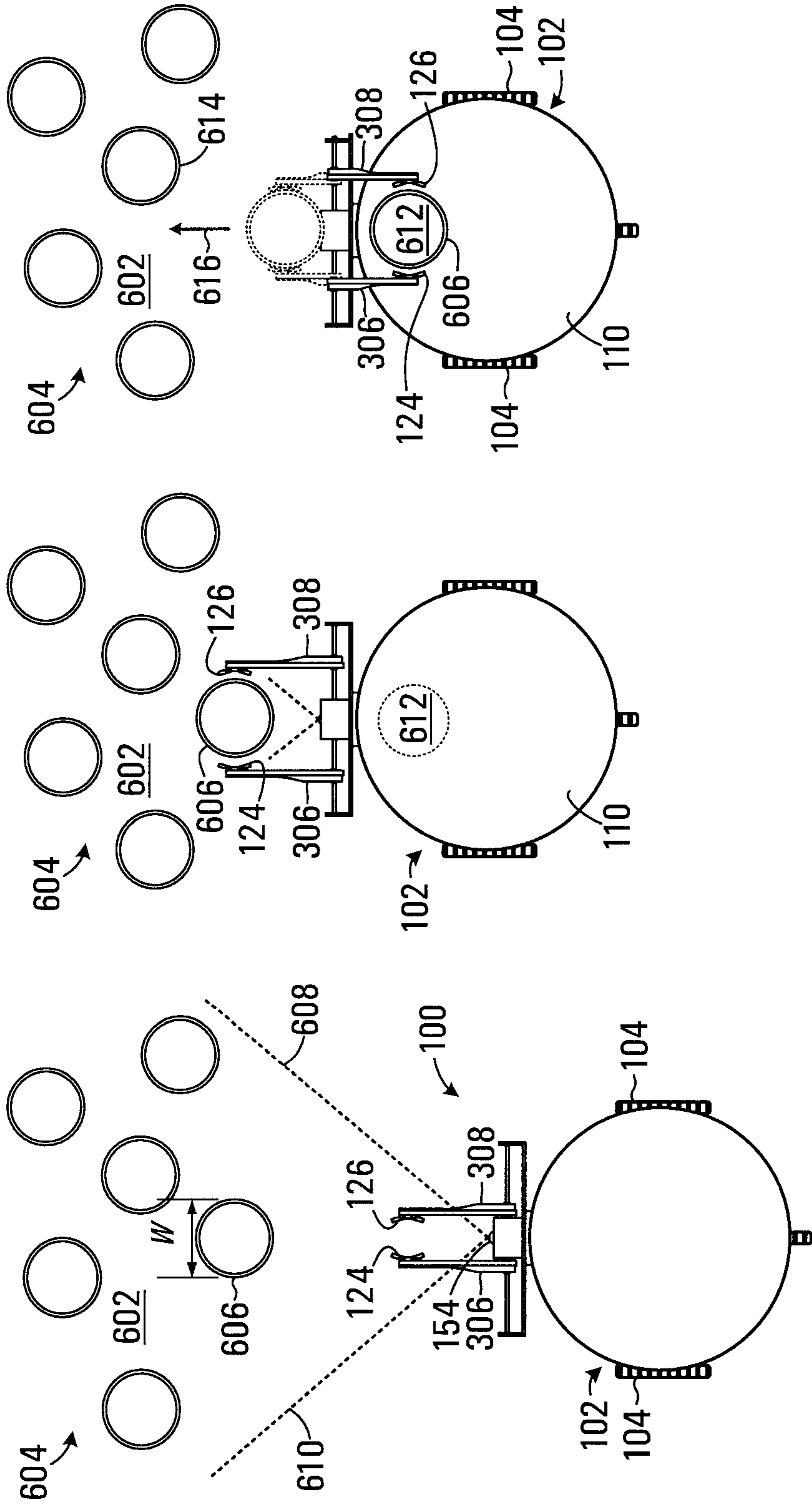


FIG. 8C

FIG. 8B

FIG. 8A



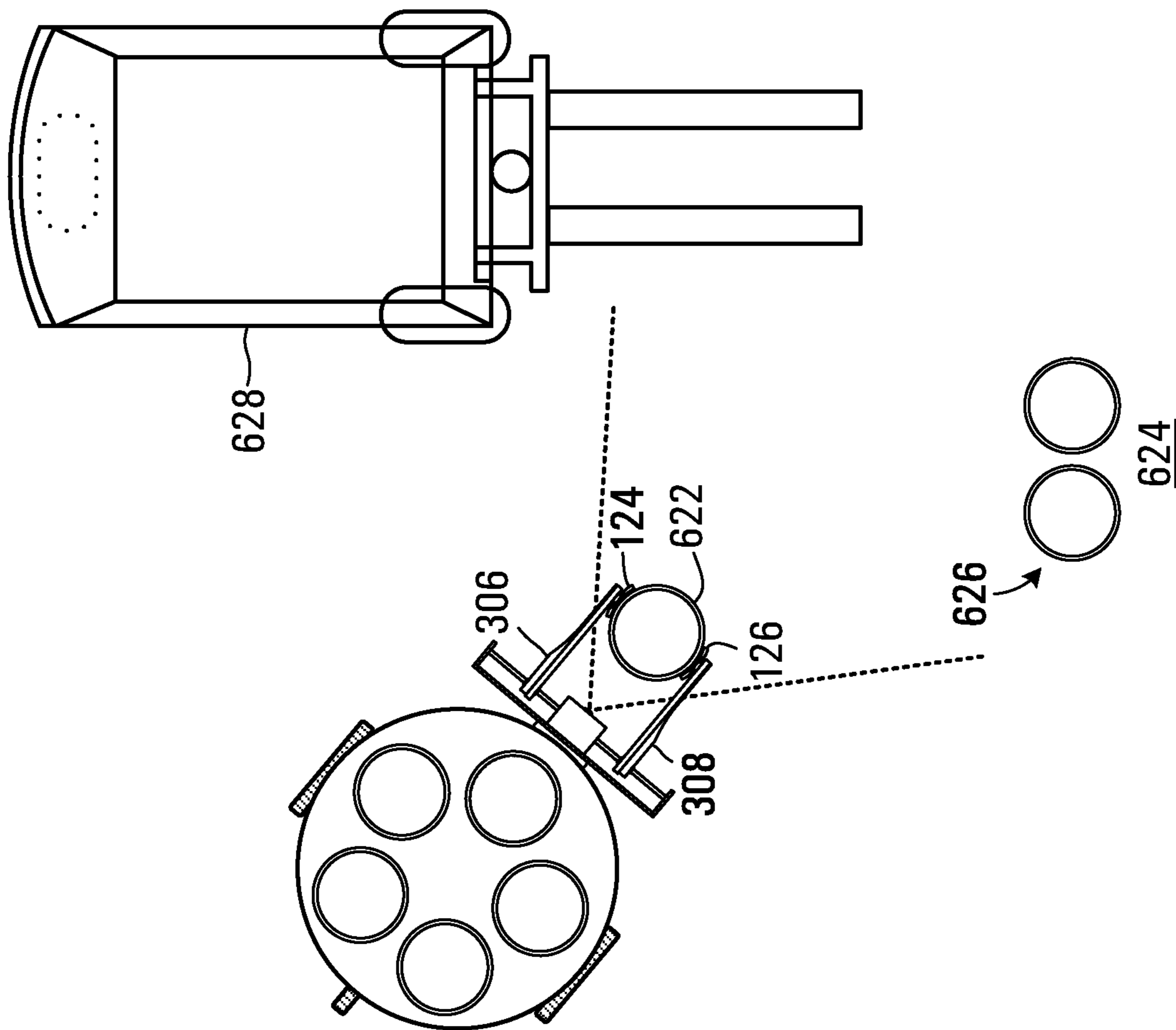


FIG. 8E

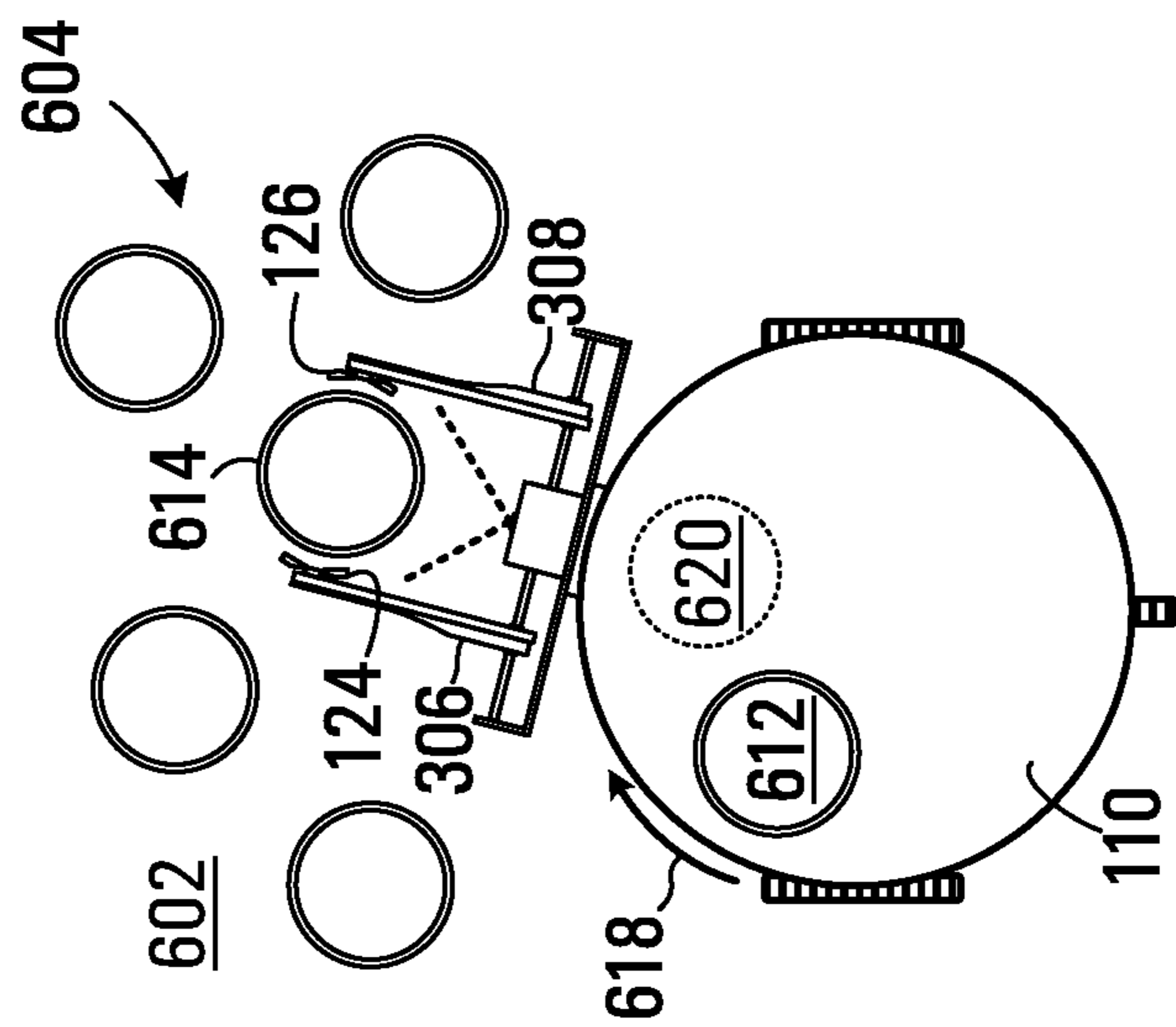


FIG. 8D

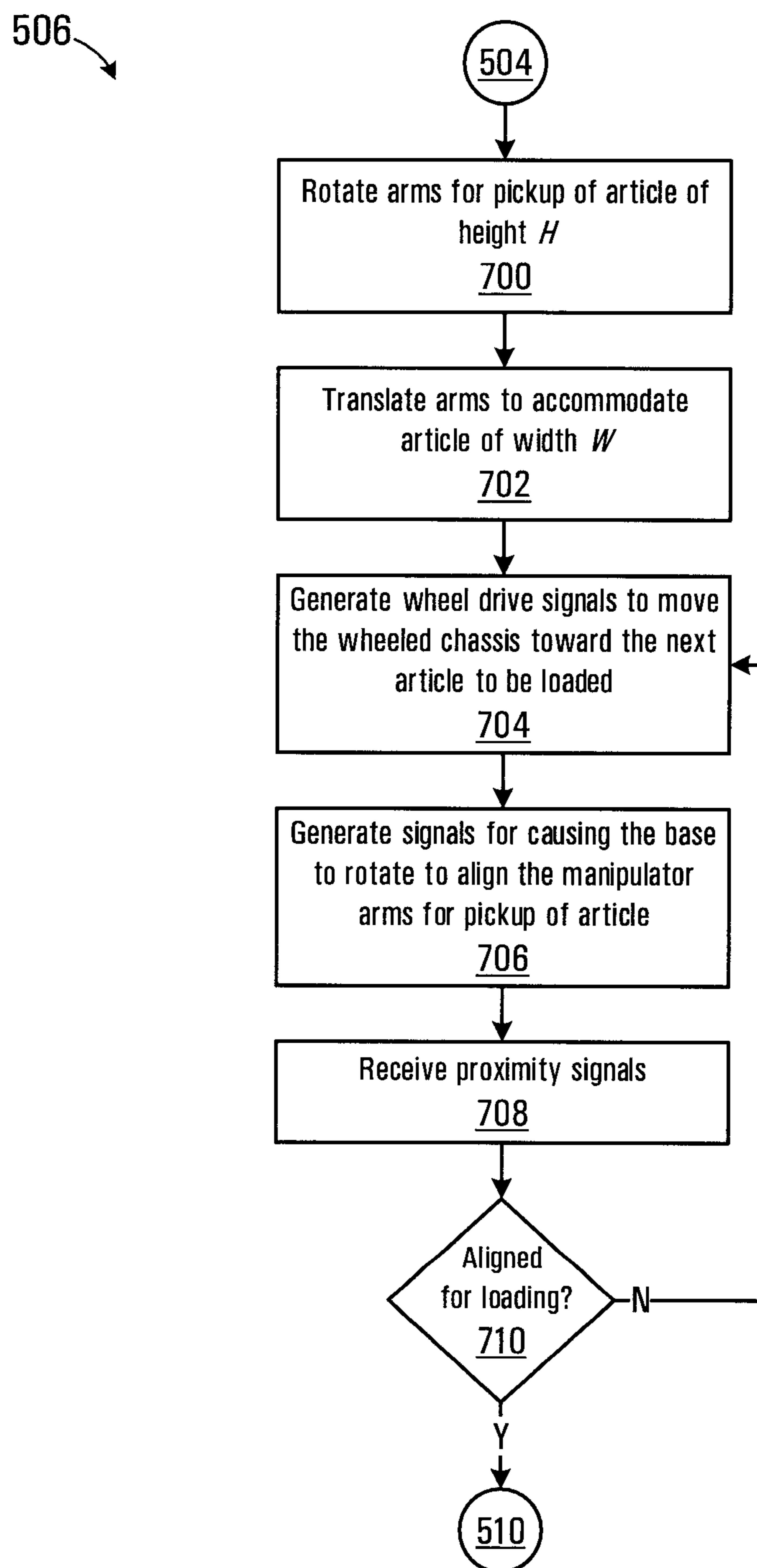


FIG. 9

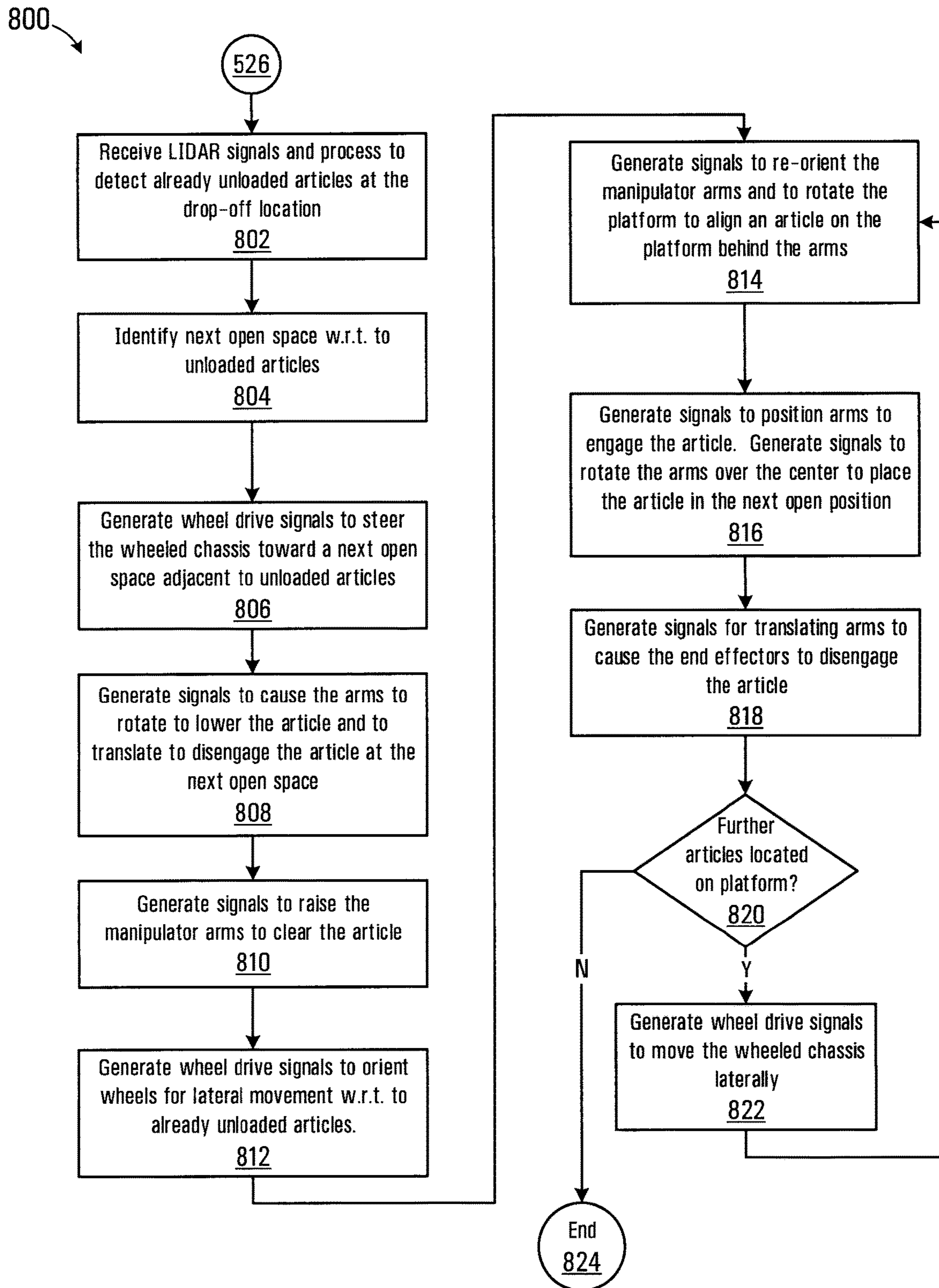


FIG. 10

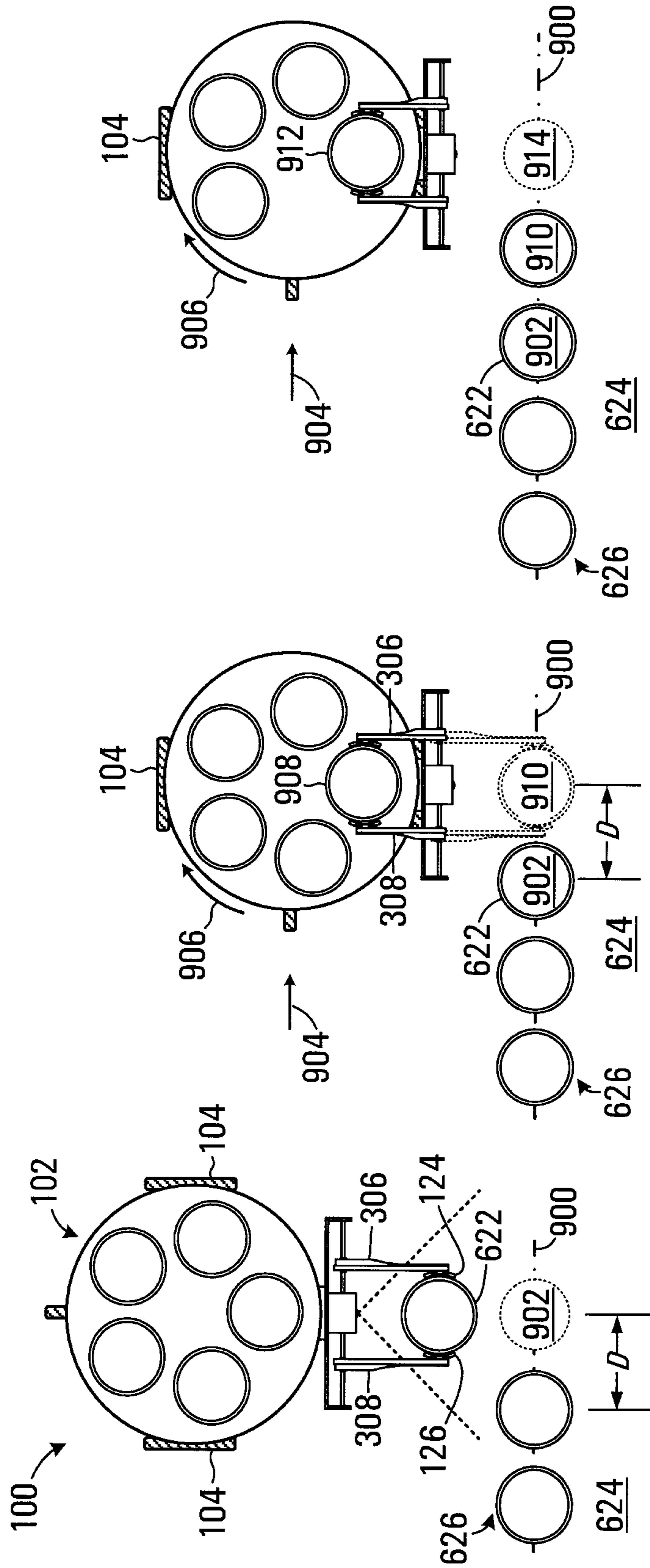


FIG. 11A

FIG. 11B

FIG. 11C

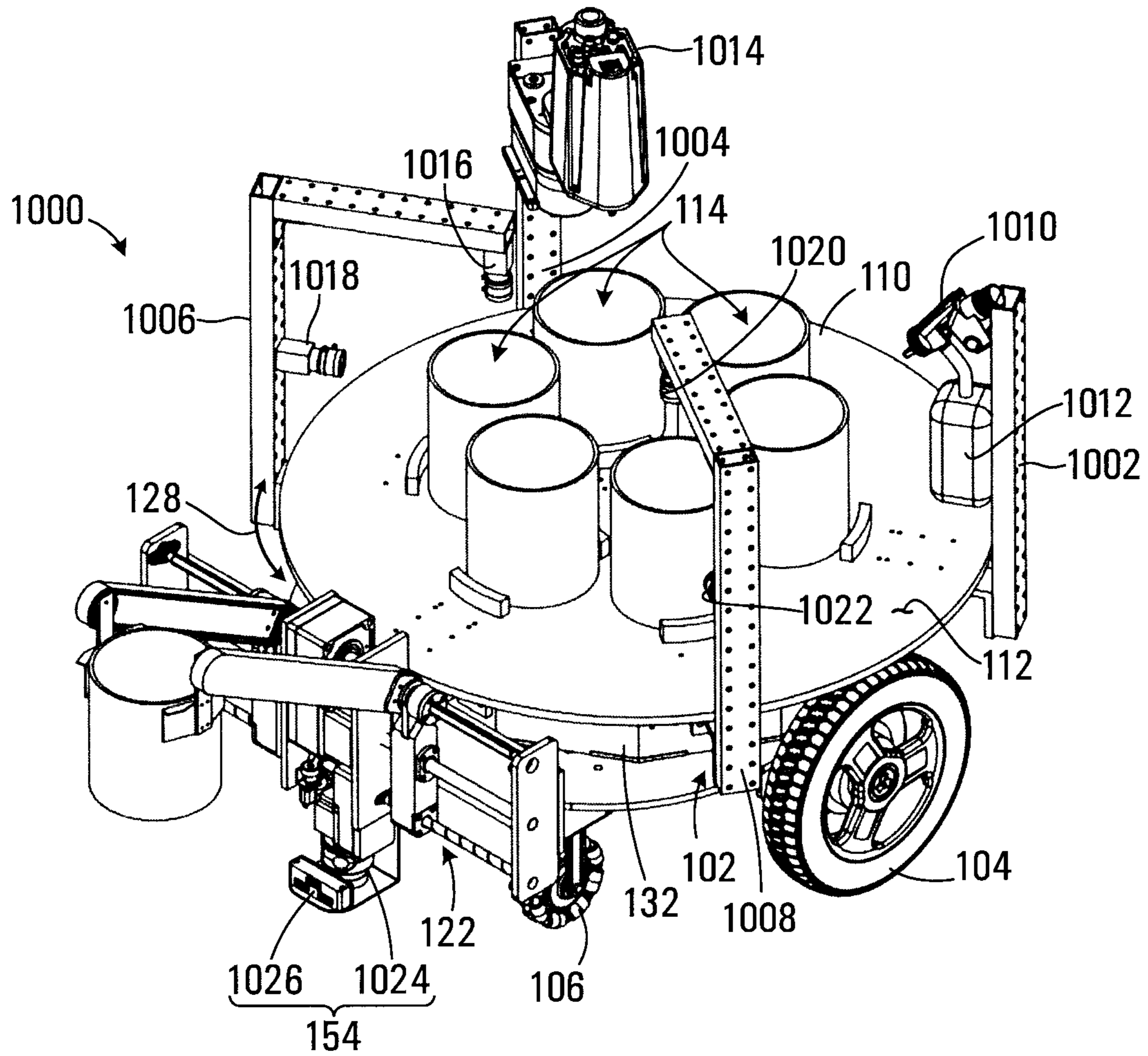


FIG. 12

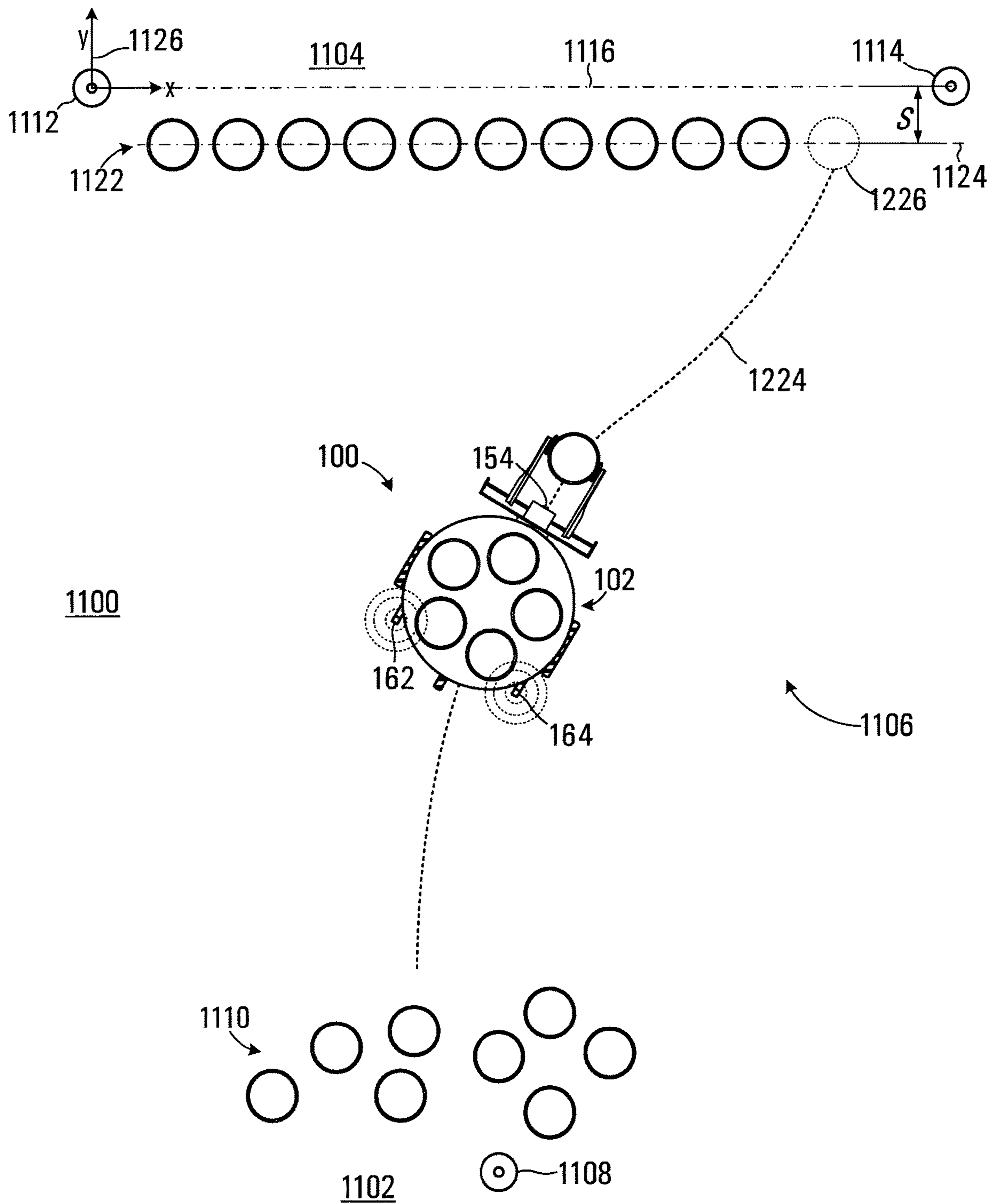
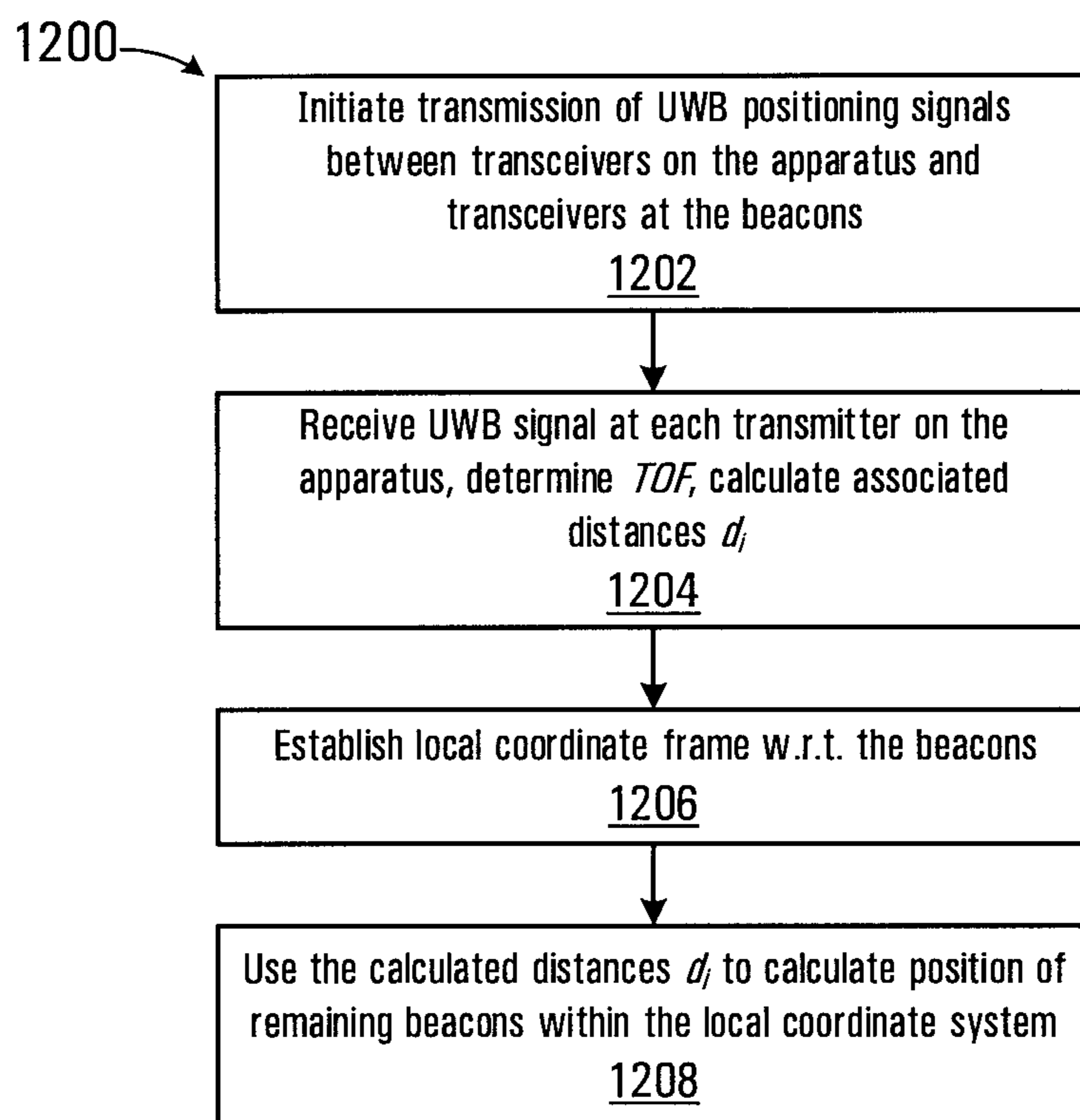
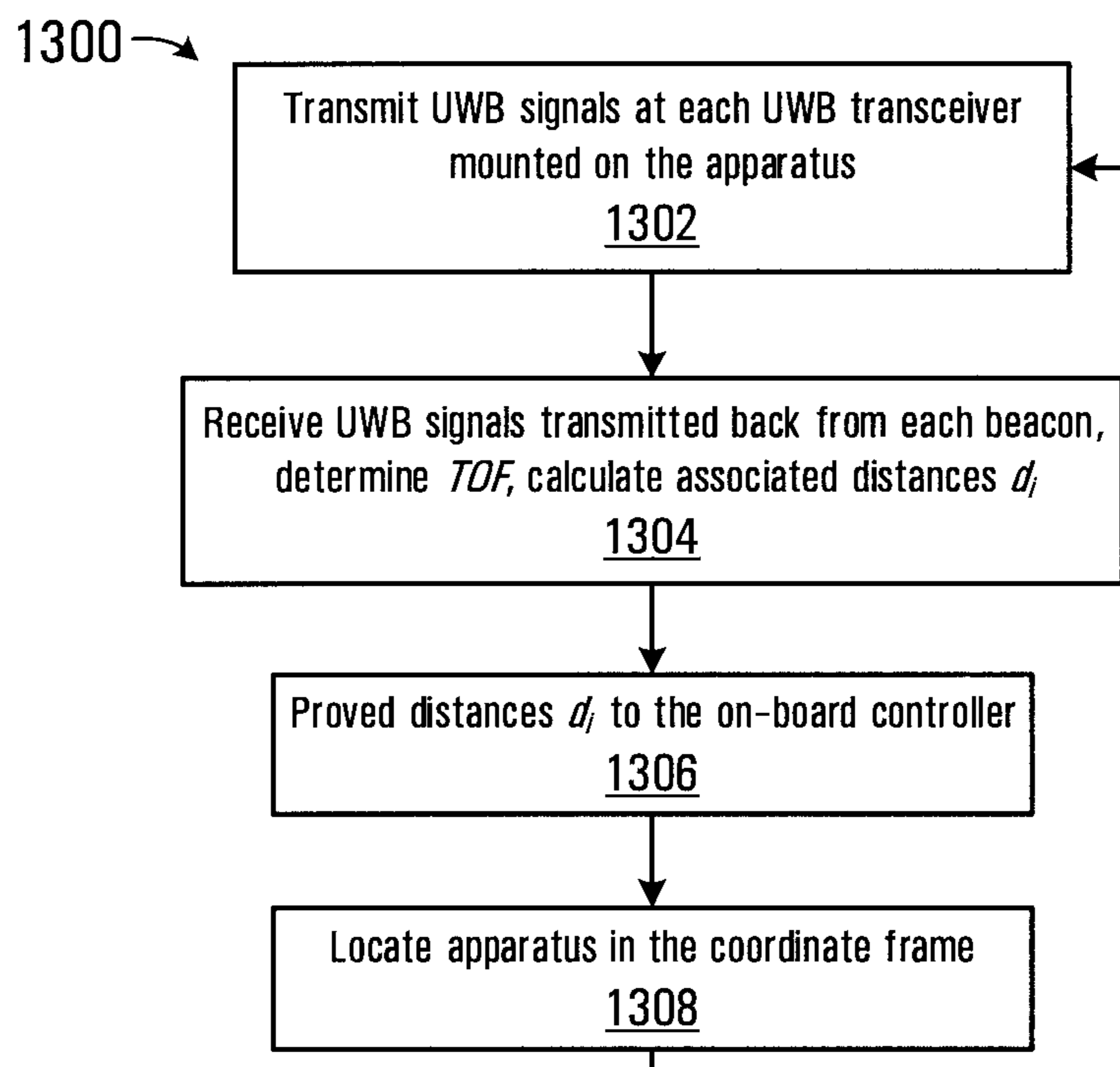


FIG. 13

**FIG. 14****FIG. 15**

**MOBILE WORK STATION FOR  
TRANSPORTING A PLURALITY OF  
ARTICLES**

RELATED APPLICATIONS

This application claims the benefit of U.S. provisional patent application 62/383,747 entitled "MULTIFUNCTIONAL UNMANNED GROUND VEHICLE", filed on Sep. 6, 2016 and incorporated herein by reference in its entirety.

BACKGROUND

1. Field

This disclosure relates generally to transporting articles and more particularly to a robotic mobile work station for transporting and performing operations on a plurality of articles.

2. Description of Related Art

Robotic vehicles may be configured for autonomous or semi-autonomous operation for a wide range of applications including product transportation, material handling, security, and military missions.

Autonomous mobile robotic vehicles typically have the ability to navigate and to detect objects automatically and may be used alongside human workers, thereby potentially reducing the cost and time required to complete otherwise inefficient operations such as basic labor, transportation and maintenance.

Some autonomous vehicles track movement of driven wheels of the vehicle using encoders to determine a position of the vehicle within a workspace.

SUMMARY

In accordance with one disclosed aspect there is provided an apparatus for transporting a plurality of articles. The apparatus includes a wheeled chassis, and a platform disposed on the wheeled chassis. The apparatus also includes a manipulator coupled to the wheeled chassis and operably configured to load a first article of the plurality of articles at a first position on the platform, or unload the first article of the plurality of articles from the first position on the platform. The apparatus further includes at least one actuator operably configured to cause successive relative rotational movements between the manipulator and the platform to provide access to successive rotationally spaced apart positions on the platform for loading or unloading each subsequent article in the plurality of articles.

The at least one actuator may be operably configured to cause one of a rotary movement of the platform about the wheeled chassis and a rotary movement of the manipulator about the wheeled chassis.

The manipulator may be coupled to base rotatable with respect to the wheeled chassis and the at least one actuator may include a base actuator operably configured to cause rotary movement of the base and the manipulator about the wheeled chassis, a platform actuator operably configured to cause rotary movement of the platform about the wheeled chassis, the base actuator and the platform actuator being operable to cause successive relative rotational movements of both the manipulator and the platform about the wheeled

chassis for providing access for loading or unloading each subsequent article in the plurality of articles.

The manipulator may be coupled to the wheeled chassis via a support and the base actuator may be operably configured to cause rotary movement of the support about the wheeled chassis.

The wheeled chassis may include at least one drive for driving wheels of the wheeled chassis and may further include a controller operably configured to cause the at least one drive to orient the wheeled chassis for movement in a direction aligned to pick up or place the plurality of articles in a line, cause the base actuator to cause rotary movement of the manipulator about the wheeled chassis to orient the manipulator for loading or unloading the plurality of articles, and cause the platform actuator to cause rotary movement of the platform to after loading each article, dispose an empty location on the platform in reach of the manipulator for loading a subsequent article, or dispose a subsequent article on the platform in reach of the manipulator for unloading.

The wheeled chassis may include a drive for driving at least one wheel of the wheeled chassis and may further include a controller operably configured to control the drive to orient the wheeled chassis to align the manipulator for loading or unloading each of the first article and the subsequent articles.

The manipulator may include a pair of outwardly directed spaced apart arms operably configured to grasp the article, an arm actuator, operably configured to vertically rotate the arms toward the platform while the article is suspended between the arms, and an end effector distally disposed on each respective arm and the end effectors may be operably configured to grasp the article and suspend the article during vertical movement of the arms.

The arms may be mounted for vertical rotation on a driven shaft and the end effectors may be coupled to the shaft via a belt such that rotation of the arms causes a respective rotation of the end effectors for maintaining an orientation of the end effectors while grasping the article.

The pair of outwardly directed spaced apart arms may be mounted for one of lateral movement and rotational movement about a pivot to cause the pair of end effectors to move to grasp or release the article.

The apparatus may include at least one tool operably configured to perform an operation on the articles while transporting the plurality of articles on the wheeled chassis.

The at least one tool may be coupled to the manipulator such that causing rotary movement between the manipulator and the platform provides access to each article for performing the operation.

The manipulator and the at least one tool may be respectively coupled to a common base mounted for rotation on the wheeled chassis such that rotary movement of the common base causes rotary movement of each of the manipulator and the at least one tool.

The at least one tool may be coupled to the wheeled chassis such that causing rotary movement between the wheeled chassis and the platform provides access to each article for performing the operation.

In accordance with another disclosed aspect there is provided a method of transporting a plurality of articles on a wheeled chassis. The method involves causing a manipulator coupled to the wheeled chassis to load a first article of the plurality of articles at a first position on a platform disposed on the wheeled chassis, or unload the first article of the plurality of articles from the first position on the platform. The method also involves causing successive relative



rotational movements between the manipulator and the platform to provide access to successive rotationally spaced apart positions on the platform, and causing the manipulator to load or unload each subsequent article of the plurality of articles to or from the successive rotationally spaced apart positions on the platform.

Causing successive relative rotational movements may involve one of causing rotary movement of the platform about the wheeled chassis and causing rotary movement of the manipulator about the wheeled chassis.

Causing successive relative rotational movements may involve causing rotary movement of both the manipulator and the platform about the wheeled chassis.

Causing rotary movement of both the manipulator and the platform about the wheeled chassis may involve causing the wheeled chassis to be aligned for movement in a direction aligned to pick up or place the plurality of articles along a line, causing rotary movement of the manipulator to orient the manipulator for loading or unloading the plurality of articles, and causing rotary movement of the platform to, after loading each article, dispose an empty location on the platform in reach of the manipulator for loading a subsequent article, or dispose a subsequent article on the platform in reach of the manipulator for unloading.

The method may involve controlling a drive associated with at least one wheel of the wheeled chassis to orient the wheeled chassis to align the manipulator for loading each of the first article and the subsequent articles.

The method may involve operating at least one tool to perform an operation on the articles while transporting the plurality of articles on the wheeled chassis.

Operating the at least one tool may involve causing rotational movement between the at least one tool and the platform to provide access to each article for performing the operation.

Causing rotational movement between the at least one tool and the platform may involve causing rotational movement of the manipulator, the at least one tool being coupled to the manipulator.

In accordance with another disclosed aspect there is provided a method for transporting a plurality of articles between a pickup location and an intended drop-off location on a wheeled chassis having a pair of transceivers disposed in spaced apart relation on the wheeled chassis. The method involves positioning a pickup beacon proximate the plurality of articles at the pickup location, positioning a left drop-off beacon and a right drop-off beacon on either side of the intended drop-off location, the left and right drop-off beacons indicating a desired alignment of the plurality of articles at the respective location, receiving location signals at transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis, processing the location signals to determine a location and orientation of the wheeled chassis with respect to the beacons, navigating the wheeled chassis using the determined location and orientation of the wheeled chassis to pick up successive articles of the plurality of articles proximate the pickup location, move between the pickup location and the drop-off location, and place articles proximate the drop-off location.

Receiving location signals may involve transmitting ultrawideband (UWB) signals at the transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis, and receiving the UWB signals at the other transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis.

Navigating may involve using the location signals to determine a real-time location and orientation for steering

the wheeled chassis along a path between the pickup location and drop-off location, receiving proximity signals indicative of obstacles in the path of the wheeled chassis, and using the received proximity signals and location signals to modify the path of the wheeled chassis to avoid detected obstacles.

Receiving the proximity signals may involve generating proximity signals using at least one of an optical sensor, an infrared sensor, light detection and ranging (LIDAR) sensor, and an ultrasonic sensor.

Receiving the proximity signals may involve receiving a first proximity signal from an infrared sensor operably configured to indicate close range obstacles, and a second proximity signal from a light detection and ranging (LIDAR) sensor indicating mid and far range obstacles.

The method of may further involve, when the path of the wheeled chassis is within a pre-determined range of the pickup location, processing the received proximity signals to determine whether obstacles in the path of the wheeled chassis correspond to any of the plurality of articles to be transported, and in response causing the wheeled chassis to steer towards one of the articles in the plurality of articles.

The method of may further involve, when path of the wheeled chassis is within a pre-determined range of the drop-off location, causing the wheeled chassis to steer to a first location defined with respect to one of the left drop-off beacon and a right drop-off beacon for unloading of a first article.

The method may involve causing the wheeled chassis to steer to successive locations defined with respect to the one of the left drop-off beacon and a right drop-off beacon for unloading of a second article and subsequent articles in the plurality of articles.

In accordance with another disclosed aspect there is provided a system for transporting a plurality of articles between a pickup location and an intended drop-off location. The system includes a wheeled chassis having a pair of transceivers disposed in spaced apart relation on the wheeled chassis, a pickup beacon positioned proximate the plurality of articles at the pickup location, a left drop-off beacon and a right drop-off beacon positioned on either side of the intended drop-off location. The left and right drop-off beacons indicate a desired alignment of the plurality of articles at the respective location, each beacon including a transceiver. The transceivers on the beacons and the pair of transceivers on the wheeled chassis are operably configured to receive location signals and process the location signals to determine a location and orientation of the wheeled chassis with respect to the beacons for navigating the wheeled chassis to pick up articles in the plurality of articles proximate the pickup location, to move between the pickup location and the drop-off location, and to place articles in the plurality of articles proximate the drop-off location.

The transceivers disposed on each beacon and the pair of transceivers on the wheeled chassis may include ultrawideband (UWB) transceivers.

The system may include at least one proximity sensor disposed on the wheeled chassis, the proximity sensor being operable to provide an indication of obstacles in the path of the wheeled chassis.

Other aspects and features will become apparent to those ordinarily skilled in the art upon review of the following description of specific disclosed embodiments in conjunction with the accompanying figures.

## BRIEF DESCRIPTION OF THE DRAWINGS

In drawings which illustrate disclosed embodiments,

FIG. 1 is a perspective view of an apparatus for transporting a plurality of articles according to a first disclosed embodiment;

FIG. 2 is a cut-away perspective view of the apparatus shown in FIG. 1;

FIG. 3 is a perspective view of a manipulator of the apparatus shown in FIG. 1;

FIG. 4 is a perspective view of an alternative manipulator embodiment for the apparatus shown in FIG. 1;

FIG. 5 is a partially exploded perspective view of the manipulator shown in FIG. 4;

FIG. 6 is a block diagram of a processor circuit for implementing an on-board controller of the apparatus shown in FIG. 1;

FIG. 7 is a flowchart depicting blocks of code for directing the processor circuit of FIG. 6 to control autonomous loading operations of the apparatus shown in FIG. 1;

FIG. 8A to 8E are a series of plan views of the apparatus shown in FIG. 1 performing the loading process shown in FIG. 7;

FIG. 9 is an alternative embodiment of a portion of the process shown in FIG. 7;

FIG. 10 is a flowchart depicting blocks of code for directing the processor circuit shown in FIG. 6 to control autonomous unloading operations of the apparatus shown in FIG. 1;

FIG. 11A to 11C are a series of plan views of the apparatus shown in FIG. 1 performing the unloading process shown in FIG. 10;

FIG. 12 is a perspective view of an apparatus for transporting a plurality of articles according to an alternative disclosed embodiment;

FIG. 13 is a plan view of a positioning system for determining a position of the apparatus shown in FIG. 1 within an area;

FIG. 14 is a flowchart depicting blocks of code for directing a controller to locate arbitrarily positioned beacons of the positioning system shown in FIG. 13; and

FIG. 15 is a flowchart depicting blocks of code for directing the controller and the processor circuit shown in FIG. 6 to locate arbitrarily positioned beacons of the positioning system.

## DETAILED DESCRIPTION

Referring to FIG. 1, an apparatus for transporting a plurality of articles according to a first disclosed embodiment is shown generally at 100. The apparatus 100 includes a wheeled chassis 102. In the embodiment shown, the wheeled chassis 102 includes a pair of drive wheels 104, a pair of front castor wheels 106 (only one of each of the pairs of wheels is visible in FIG. 1), and a further rear castor wheel (not visible in FIG. 1 but shown at 108 in FIG. 2). The castor wheels 106 and 108 are able to swivel to permit the wheeled chassis 102 to move in a direction determined by the drive provided to the pair of drive wheels 104. The wheeled chassis 102 has a rounded shape, but in other embodiments may be otherwise shaped.

The apparatus 100 also includes a platform 110 disposed on the wheeled chassis 102. The platform 110 has an upper surface 112 for receiving a plurality of articles 114 to be transported. In FIG. 1, two articles 116 and 118 of a plurality of articles 114 have been received on the platform 110 and a third article 120 is about to be loaded onto the platform

110. The apparatus 100 also includes a manipulator 122 coupled to the wheeled chassis 102. The manipulator 122 has a pair of end effectors 124 and 126 for grasping the article 120. The movements of the end effectors 124 and 126 are actuated by actuators housed in an actuator housing 152. In other applications, the pair of end effectors 124 and 126 may be otherwise configured in accordance with the articles to be loaded and unloaded.

In operation, the apparatus 100 is configured to permit successive relative rotational movements between the manipulator 122 and the platform 110 in a direction indicated by the arrow 128. The successive relative rotational movements provide access for loading each subsequent article in the plurality of articles 114 onto the platform 110 at successive rotationally spaced apart positions. For example, as shown in FIG. 1, the platform 110 has been positioned to permit access to a position 130 for receiving the article 120. The platform 110 may have a pair of article supports 131 at each position such as shown for the position 130 in FIG. 1.

In the embodiment shown the plurality of articles 114 are plant pots and the apparatus 100 may be used in a plant nursery. Another application of the apparatus 100 may involve transporting blood samples from one location to another within a health care facility.

The apparatus 100 is shown with the platform 110 partially cut away in FIG. 2. Referring to FIG. 2, in this embodiment the apparatus 100 includes a base 132 coupled to the wheeled chassis. The platform 110 includes a gear 134 coupled to an underside 137 of the platform 110. The gear 134 and platform are mounted via a shaft 138 to the base 132. The apparatus 100 also includes a platform actuator 140 for providing a rotation torque to a drive gear 136 that meshes with the gear 134. The platform actuator 140 includes a rotational encoder (not shown) that measures the angular rotation of the platform 110. In this embodiment the platform actuator 140 is implemented using an electrical motor that generates a torque for causing rotational movement of the drive gear 136, which in turn causes the gear 134 and the platform 110 to rotate about the shaft 138 in the direction 128 with respect to the base 132.

In the embodiment shown, the base 132 is also rotatable with respect to the wheeled chassis 102 and includes a gear 142 coupled to the wheeled chassis. The base 132 includes a base actuator 144 having a drive gear 146 that engages with the gear 142. In this embodiment the base actuator 144 is implemented using an electrical motor that generates a torque for causing rotational movement of the drive gear 146, which causes the base 132 to rotate about the gear 142, and thus the wheeled chassis 102, in a direction indicated by the arrow 148. The base actuator 144 is mounted to a cover plate 149 (shown partially cut away in FIG. 2) that covers the base 132. The base actuator 144 includes a rotational encoder 151 for measuring the angular rotation of the base 132. The cover plate 149, which is shown cut away in FIG. 2, extends across and covers the base 132 and carries a plurality of rollers (of which a roller 153 is shown in FIG. 2). The rollers are distributed peripherally on the cover plate and support the underside 137 platform 110 during loading, transporting, and unloading operations.

In this embodiment, the manipulator 122 is coupled to and moves with the base 132. Since the platform 110 is also coupled to the base 132, the platform will move in the direction 148 when the base moves and relative rotational movements of the platform 110 with respect to the base are actuated by causing the platform actuator 140 to drive the drive gear 136.

In other embodiments the platform **110** and base **132** may be independently rotatable relative to the wheeled chassis **102**. Alternatively, in some embodiments the base **132** may be fixed to the wheeled chassis and not able to rotate independently of the wheeled chassis **102**.

In the embodiment shown in FIG. 1 and FIG. 2 both of the pair of the wheels **104** are independently driven by a hub drive **150**. The front castor wheels **106** and rear castor wheel **108** are not driven but rather provide stability for the wheeled chassis **102**. In other embodiments the pair of driven wheels **104** may have a common drive and one of the castor wheels **106** and **108** may be steerable.

The apparatus **100** also includes a proximity sensor **154**, which is operable to provide an indication of obstacles in the path of the wheeled chassis **102**. In the embodiment shown the proximity sensor **154** is implemented using an optical light detection and ranging (LIDAR) sensor. Other proximity sensors such as an infrared sensor or ultrasonic sensor may be alternatively or additionally used to implement the proximity sensor **154**.

The manipulator **122** is shown in isolation in FIG. 3 with a cover (shown in FIG. 2) of the actuator housing **152** removed to reveal details of actuators for activating movements of the manipulator. Referring to FIG. 3, the manipulator **122** includes a frame **300**, a pair of endplates **302** and **304**. In the embodiment shown, the end effectors **124** and **126** are coupled to respective arms **306** and **308**. Each arm **306** and **308** is mounted for rotation on a respective spline shaft **310** and **312**. The manipulator **122** also includes an arm actuator **314**, which is coupled to the respective spline shafts **310** and **312**. The spline shaft **310** extends between a bearing **316** mounted on the endplate **302** and the actuator housing **152** and is coupled to the arm actuator **314**. Similarly, the spline shaft **312** extends between a bearing **318** mounted on the endplate **304** and the actuator housing **152** and is also coupled to the arm actuator **314**.

The arm actuator **314** is operable to generate a rotational torque on the spline shafts **310** and **312** for causing the arms **306** and **308** to be rotated about the shafts for raising or lowering the respective end effectors **124** and **126**. The arm actuator **314** includes an encoder (not shown) that provides a measurement of the rotational position of the spline shafts **310** and **312** and thus the arms **306** and **308**. In the embodiment shown, the end effectors **124** and **126** are mounted on a pulley belt **320**, which is coupled to between a pulley wheel on the spline shaft **312** (not shown) and a pulley wheel **322**. When the pulley wheel on the spline shaft **312** rotates, the pulley belt **320** causes a corresponding synchronous rotation of the pulley wheel **322** such that the end effector **126** remains in the orientation shown (i.e. generally vertically oriented) when the arm **308** is raised or lowered. The arm **306** is similarly configured.

The manipulator **122** also includes a guide rod **324** extending between the endplate **302** and the actuator housing **152** and a guide rod **326** extending between the endplate **304** and the actuator housing. The arms **306** and **308** are coupled to respective linear guides **328** and **330** that are received on the respective guide rods **324** and **326**. The linear guides **328** and **330** facilitate translational movements of the arms **306** and **308** along the respective guide rods **324** and **326**. The manipulator **122** further includes a leadscrew **332**, a leadscrew **334**, and a translation actuator **336**. The leadscrew **332** extends between a bearing **338** mounted on the endplate **302** and the actuator housing **152** and is coupled to the translation actuator **336**. Similarly, the leadscrew **334** extends between a bearing **340** mounted on the endplate **304** and the actuator housing **152** and is coupled to the transla-

tion actuator **336**. Each linear guide **328** and **330** has a leadscrew nut (only the leadscrew nut **342** associated with the guide **328** is visible in FIG. 3), which is received on the respective leadscrews for causing translational movement of the linear guides to reduce or increase a lateral distance between the pair of end effectors **124** and **126** for accommodating different sized articles. In this embodiment the leadscrew **332** and leadscrew **334** have opposite thread directions, such that rotation of the respective leadscrews by the translation actuator **336** causes opposite movements of the respective linear guides **328** and **330** along the guide rods **324** and **326**. The translation actuator **336** includes a rotary encoder (not shown) that provides a measurement of the rotational drive provided to the leadscrews **332** and **334**, which is converted into a linear translation distance based on the leadscrew thread pitch.

An alternative manipulator embodiment is shown in FIG. 4 at **450**. Referring to FIG. 4, the manipulator **450** includes a frame **452**, which attaches to the apparatus **100** via a bracket **454**. The manipulator **450** includes a pair of arms **456** and **458** having respective end effectors **460** and **462**. Further details of the manipulator **450** are shown in the partially exploded view of FIG. 5. Referring to FIG. 5, the arms **456** and **458** are similarly configured to the arms **306** and **308** shown in FIG. 3, and include a pulley belt **464** coupled to between pulley wheels **466** and **468** for providing synchronous rotation such that the end effectors **460** and **462** maintain their orientation when the arms are raised or lowered.

The manipulator **450** includes pivots **470** and **472** mounted on the frame **452** for pivotably mounting each of the arms **456** and **458**. In FIG. 5, the arm **456** is shown removed from the pivot **470** to better show details of the manipulator **450**. The pivot **470** has a vertically extending portion **474** for engaging a channel (not shown) in the pulley wheel **466** such that the pulley wheel is able to rotate freely about the vertically extending portion of the pivot in a direction indicated by the arrow **476**. The manipulator **450** also includes an arm actuator **478** operable to raise or lower the arms **456** and **458** by causing rotation of a shaft **480**, which is coupled to arm mounting brackets **482** and **484**. When the shaft **480** causes the arm **456** to be raised or lowered, the vertically extending portion **474** of the pivot **470** prevents the pulley **466** from rotating and the pulley belt **464** is moved causing a rotational movement to the pulley wheel **468** in proportion to the upward or downward movement of the arm. In this manner, the end effector **460** remains oriented as shown in FIG. 4 when the arm is raised or lowered. The arm **458** is configured in the same way.

The manipulator **450** also includes respective stepper motors **486** and **488** for causing lateral rotation of the respective arms **456** and **458**. The stepper motor **488** associated with the arm **458** is shown with an outer covering removed in FIG. 5. The stepper motor is coupled via a drive shaft **490** to a beam **492** of the arm **458** and causes lateral rotation of the beam and arm about the drive shaft in a direction shown by the arrow **494**.

The manipulator **450** thus differs from the manipulator **122** in that the arms **456** and **458** are configured for a “pincer” type movement for gripping and releasing articles rather than for a lateral translation as in the case of the arms **306** and **308**.

Referring back to FIG. 2, in the embodiment shown the apparatus **100** further includes an on-board controller **160** for autonomously controlling operations of the apparatus. The controller **160** is shown in more detail in FIG. 6 and may be implemented using an embedded processor circuit such

as a Microsoft Windows® industrial PC. Referring to FIG. 6, the controller 160 includes a microprocessor 400, a memory 402, and an input output (I/O) 404, all of which are in communication with the microprocessor 400. The I/O 404 includes a wireless interface 406 (such as an IEEE 802.11 interface) for wirelessly receiving and transmitting data communication signals between the controller 160 and a network 408. The I/O 404 also includes a wired network interface 410 (such as an Ethernet interface) for connecting to the LIDAR proximity sensor 154. The I/O 404 further includes a USB interface 412 for connecting to a digital to analog converter (DAC) 414 and to ultra-wideband transceivers (UWB) 416 and 417.

The DAC 414 includes a plurality of ports for receiving analog signals and converting the analog signals into digital data representing the signals and/or producing analog control signals. In the embodiment shown the DAC 414 includes a port 418 for producing control signals for controlling the platform actuator 140. The rotary encoder of the platform actuator 140 produces a signal indicating a rotational position of the platform 110, which are received at the port 418. The DAC 414 also includes a port 420 for producing control signals for controlling the base actuator 144. The rotational encoder 151 of the base actuator 144 produces a signal indicating a rotational position of the base 132, which are received at the port 420. The DAC 414 also includes a port 422 for producing control signals for controlling the arm actuator 314 and a port 424 for producing control signals for controlling the translation actuator 336 of the manipulator 122. Signals from the encoders associated with the actuators 314 and 336 are received at the respective ports 422 and 424. The DAC 414 also includes a port 426 for producing control signals for controlling the hub drives 150 of the respective drive wheels 104 for moving and steering the wheeled chassis 102 of the apparatus 100.

Program codes for directing the microprocessor 400 to carry out various functions are stored in a location 430 of the memory 402, which may be implemented as a flash memory, for example. The program codes 430 direct the microprocessor 400 to implement an operating system (such as Microsoft Windows for example) and to perform various other system functions associated with operation of the apparatus 100. The memory 402 also includes variable storage locations 432 for storing variable and parameter data associated with operation of the apparatus 100.

In other embodiments (not shown), the controller 160 may be partly or fully implemented using a hardware logic circuit including discrete logic circuits, an application specific integrated circuit (ASIC), and/or a field-programmable gate array (FPGA), for example.

Referring to FIG. 7, a flowchart depicting blocks of code for directing the controller processor circuit 160 to control autonomous loading operations of the apparatus 100 is shown at 500. The blocks generally represent codes that may be read from the program codes location 430 of the memory 402 for directing the microprocessor 400 to perform various loading functions. The actual code to implement each block may be written in any suitable program language, such as C, C++, C#, Java, and/or assembly code, for example.

A plan view of the apparatus 100 performing the loading process 500 is provided in FIGS. 8A-8F as an example of a typical loading operation for the apparatus 100. The loading process 500 starts at block 502, which directs the microprocessor 400 to receive signals produced by the LIDAR proximity sensor 154 at the wired network interface 410 of the I/O 404. Referring to FIG. 8A, a plurality of articles to be loaded at a pickup location 602 is shown generally at 604.

The LIDAR proximity sensor 154 is operable to detect articles within a range of angles indicated by broken lines 608 and 610 in FIG. 8A. In one embodiment, standard dimensions for articles to be loaded are stored in the memory 402 (for example a height H and a width W) and block 502 directs the microprocessor 400 read the H and W values and to determine whether the received LIDAR signals include data that corresponds to these dimensions. Articles that generate LIDAR data signals that generally match the standard dimensions are identified as articles to be loaded at the pickup location 602.

Block 504 directs the microprocessor 400 to output signals at the USB interface 412 of the I/O 404, which cause the DAC 414 to generate wheel drive signals at the port 426 for controlling the respective hub drives 150 of the drive wheels 104. The generated drive signals control the respective hub drives 150 for steering the wheeled chassis 102 toward a first detected article 606 of the plurality of articles 604.

Block 506 then directs the microprocessor 400 to cause the DAC 414 to produce signals at the port 422 for causing the arms 306 and 308 to be positioned for loading by causing the arm translation actuator 336 to translate the arms outwardly to accommodate the width of the detected article. Block 506 also directs the microprocessor 400 to cause the DAC 414 to produce signals at the port 422 for causing the arm rotation actuator 314 rotate the arms 306 and 308 about the spline shafts 310 and 312 until the end effectors 124 and 126 are positioned at height corresponding to the height H of the article 604. Referring to FIG. 8B, in this embodiment the when positioned for loading, the arms 306 and 308 are spaced apart at a distance slightly exceeding the width W of the article 606, either based on the standard dimensions saved in memory 402 or based on a measured dimension of the article from the LIDAR data.

Block 508 then directs the microprocessor 400 to generate wheel drive signals at the port 426 to advance and steer the wheeled chassis 102 to align the arms 306 and 308 such that the respective end effectors 124 and 126 are aligned to grasp the article 606 at diametrically opposing surfaces thereof, as shown in FIG. 8B. Block 510 then directs the microprocessor 400 to cause the DAC 414 to produce signals at the port 422 for causing the arms 306 and 308 to translate inwardly to engage the article 606.

The loading process 500 then continues at block 512, which directs the microprocessor 400 to determine whether there is a vacant loading position available on the platform 110. If there is a vacant loading position available (in the example shown in FIG. 8B the platform is empty), then the microprocessor 400 is directed to block 514. In one embodiment, the number of positions on the platform 110 than can be occupied by articles 604 is determined based on the width W of the articles. A register of the number of positions already filled may also be stored in memory 402, and used by the microprocessor 400 to determine whether there is a vacant position remaining on the platform 110.

Block 514 directs the microprocessor 400 to cause the DAC 414 to generate platform actuation signals at the port 418 for causing the platform 110 to rotate to align a vacant position 612 (shown in broken outline) behind the arms 306 and 308 of the manipulator 122. In the example shown in FIG. 8B, since the platform 110 is empty, no rotational movement of the platform is necessary, but if any articles had already been loaded the platform would need to be rotated to align a vacant position behind the arms 306 and 308 of the manipulator 122.

While blocks 512 and 514 are depicted as following sequentially after blocks 502-510, in practice the functions

## 11

of these blocks may be performed in parallel with other functions. Similarly, the functions of blocks 506 and 510 may also be performed in parallel with functions 504 and 508.

Block 516 then directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 422 to cause the arm rotation actuator 314 to rotate the arms 306 and 308 upwardly about the spline shafts 310 and 312 towards the platform 110 (as shown in broken outline in FIG. 8C) and over the center toward the vacant position 612 on the platform 110.

Block 518 then directs the microprocessor 400 to cause the DAC 414 to produce signals at the port 424 for causing the arm translation actuator 336 to translate the arms 306 and 308 outwardly to disengage the article 606, as shown in FIG. 8C. Block 518 also direct the microprocessor 400 to return the arms to the loading position by causing the DAC 414 to output signals for causing the arm actuator 314 to rotate the arms 306 and 308 back to the forward oriented position as shown in FIG. 8B. Block 518 may also cause blocks 512 and 514 to be repeated to cause the platform actuator 140 to rotate the platform 110 to align a vacant position for loading the next article behind the arms 306 and 308 of the manipulator.

The loading process 500 then continues at block 520, which directs the microprocessor 400 to receive signals produced by the LIDAR proximity sensor 154 at the wired network interface 410 of the I/O 404. Block 522 then directs the microprocessor 400 to determine whether further articles are detected, in which case block 522 directs the microprocessor back to block 504 to repeat blocks 504-512. If no further articles are detected, then block 522 directs the microprocessor 400 to block 526, which causes the DAC 414 to generate wheel drive signals at the port 426 for steering the wheeled chassis 102 toward a drop-off location (not shown in FIG. 8).

If at block 512, there is no vacant loading position on the platform 110, the microprocessor 400 is directed to block 524. Block 524 directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 422 for causing the arm actuator 314 to elevate the article 606 off the ground and to hold the article in the arms for transport. Advantageously, even though there are no vacant positions on the platform 110, an additional article may be carried in the pair of end effectors 124 and 126. Block 526 then directs the microprocessor 400 to cause the DAC 414 to generate wheel drive signals at the port 426 for steering the wheeled chassis 102 toward a drop-off location (not shown in FIG. 8).

In the process 500 as described above, the platform actuator 140 positions the platform 110 such that successive vacant loading positions on the platform are disposed to receive articles 604. Additionally or alternatively, the base actuator 144 may be actuated together with the platform actuator 140 at block 506 to facilitate efficient movement of loading of articles. An alternative embodiment of the functions implemented at block 506 is shown in FIG. 9. Referring back to FIG. 8C, following loading of the article 606, the LIDAR proximity sensor 154 may detect an article 614 in the plurality of articles 604 as the next article to be loaded. Referring to FIG. 9, block 700 directs the microprocessor 400 to cause the DAC 414 to generate signals for rotating the arms 306 and 306 to a correct loading height H for picking up the article 614 and block 702 directs the microprocessor 400 to cause the DAC 414 to generate signals for translating the arms 306 and 306 to a correct width W for engaging the article 614.

## 12

Block 704 then directs the microprocessor 400 to cause the DAC 414 to generate wheel drive signals at the port 426 to move the wheeled chassis toward the article 614. As shown in FIG. 8C, the wheels remain oriented to move the wheeled chassis 102 in a direction indicated by the arrow 616. Referring to FIG. 8D, and FIG. 9, block 706 then directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 420 for causing the base actuator 144 to rotate the base 132 and the attached manipulator 122 in the direction indicated by the arrow 618. Block 708 then directs the microprocessor 400 to receive proximity signals from the proximity sensor 154 at the wired network interface 410 of the I/O 404. Block 710 then directs the microprocessor 400 to determine whether the apparatus 100 is aligned for loading of the article 614. If at block 710 the apparatus 100 is not yet aligned for loading of the article 614, block 710 directs the microprocessor back to block 704 and blocks 704-708 are repeated to perform further movement iterations until at block 710, it is determined that the apparatus is aligned for loading as shown in FIG. 8D. While blocks 704 and 708 are shown being sequential in FIG. 9, the movement functions could also be performed in parallel. The article 614 is then loaded into a vacant position 620 as described above in connection with blocks 512-520 or blocks 524 and 526. When the platform 110 is rotated to place the vacant position 620 behind the manipulator arms 306 and 308, the rotation of the base 132 is taken into account and the loading operation thus involves coordinated movements of the wheeled chassis 102, base 132, and platform 110. Block 710 then directs the microprocessor 400 to block 510 of the process 500, where the microprocessor is directed to cause the DAC 414 to produce signals at the port 422 for causing the arms 306 and 308 to translate inwardly to engage the article.

Referring to FIG. 8E, on completion of the process loading process 500, the platform 110 has 5 of the plurality of articles 604 loaded on the platform 110 and a sixth article 622 held for transport in end effectors 124 and 126. As described above, block 526 directs the microprocessor 400 to generate wheel drive signals to steer the wheeled chassis toward a drop-off location 624. In the embodiment shown in FIG. 8E, two articles 626 have already been dropped off at the drop-off location 624. The on-board controller 160 monitors signals produced by the LIDAR proximity sensor 154 to avoid colliding with any obstacles, such as a forklift truck 628.

Referring to FIG. 10, a flowchart depicting blocks of code for directing the controller processor circuit 160 to control autonomous unloading operations of the apparatus 100 is shown at 800. The process begins at block 802, which directs the microprocessor 400 to receive LIDAR signals from the proximity sensor 154 at the wired network interface 410 of the I/O 404 and to process the signals to detect already unloaded articles at the drop-off location 624.

Two articles 626 have already been unloaded at the drop-off location 624. Block 804 then directs the microprocessor 400 to identify a next open space with respect to the articles 626. Referring to FIG. 11A, in the embodiment shown articles are to be spaced apart by a distance D and aligned along a datum line 900. The distance D may be calculated based on the width W of the articles and such that there remains sufficient space between adjacent articles to permit the end effectors 124 and 126 to be maneuvered. The next open space is identified at 902, and block 806 directs the microprocessor 400 to cause the DAC 414 to generate wheel drive signals at the port 426 to cause the wheeled chassis 102 to move toward the next open space 902 and to

position the article 622 (held in the end effectors 124 and 126) above the open space. Block 808 then directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 422 to cause the arms 306 and 308 to rotate to lower the article 622 into the open space 902. Block 808 also directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 424 to translate the arms 306 and 308 outwardly to disengage the article 622.

Block 810 then directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 422 to cause the arms 306 and 308 to be raised to clear the article. Block 812 then directs the microprocessor 400 to cause the DAC 414 to generate wheel drive signals to orient the wheeled chassis 102 for lateral movement in a direction 904 aligned with the datum line 900 along which the already unloaded articles 626 and 622 are aligned. Block 814 then directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 420 to cause the base actuator 144 to rotate the base 132 to re-orient the manipulator 122 toward the articles 626 as shown in FIG. 11B. Block 814 further directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 418 to cause the platform actuator 140 to rotate the platform 110 in a direction indicated by the arrow 906 to align an article 908 on the platform behind the manipulator 122. Block 816 then directs the microprocessor 400 to cause the DAC 414 to produce signals at the port 422 to align the arms 306 and 308 such that the respective end effectors 124 and 126 are aligned to grasp the article 908 at diametrically opposing surfaces thereof, as shown in FIG. 11B. Block 816 also directs the microprocessor 400 to cause the DAC 414 to produce signals at the port 424 to cause the end effectors 124 and 126 to grasp the article 908, and to produce signals at the port 422 to lift the article over the center and lower the article into a next open space 910. Block 818 then directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 424 to translate the arms 306 and 308 outwardly to disengage the article 908. The article 908 is again aligned with the datum line 900 and placed a distance D from the article 622.

The process 800 then continues at block 820, which directs the microprocessor 400 to determine whether there are further articles remaining on the platform to be unloaded. As described above, a register for the number of loaded articles is stored in the memory 402 and is read and updated by the microprocessor each time an article is unloaded from the platform 110. If at block 820 further articles are still to be unloaded, the microprocessor 400 is directed to block 822, which directs the microprocessor to cause the DAC 414 to generate wheel drive signals at the port 426 to cause a further lateral movement corresponding to the distance D in the direction 904 for unloading the next article into an open space 914. Block 822 then directs the microprocessor 400 back to block 814 and blocks 814-820 are repeated for each remaining article on the platform 110.

If at block 820, no further articles remain on the platform, then the unloading process ends at 824. In the embodiment shown, the combination of the rotatable base 132 and rotatable platform 110 advantageously allow orientation of the wheels 104 for movement in the direction 904. Subsequent lateral movements of the wheeled chassis 102 by the distance D facilitate rapid unloading of articles from the platform. In embodiments having a fixed base 132, following placement of the article in the open space 902, each subsequent unload would require a reversing movement of the wheeled chassis 102 to clear the unloaded article followed by a forward movement of the wheeled chassis to align with the next open space.

In the embodiment shown in FIGS. 11A-11C, the articles are aligned along a single datum line 900. In other embodiments, articles may be unloaded to align with a plurality of spaced apart datum lines such that articles are placed in several rows. The autonomous unloading operations of the apparatus 100 result in a precise alignment of the articles and also precise spacing D between articles. The precise alignment and spacing provided by the autonomous unloading has the advantage of conserving space at the drop-off location 624, which may accommodate a greater number of articles than if manually placed.

An alternative embodiment of an apparatus for transporting a plurality of articles is shown in FIG. 12 at 1000. Referring to FIG. 12, the apparatus 1000 includes all of the components of the apparatus 100 shown in FIG. 1, including the wheeled chassis 102 having drive wheels 104 and castor wheels 106, the base 132 and platform 110, and the manipulator 122. The apparatus 1000 further includes one or more tools operably configured to perform an operation on the plurality of articles 114 while being transported on the wheeled chassis 102. In the embodiment shown, a plurality of tool supports 1002, 1004, 1006, and 1008 are coupled to the base 132. The tool support 1002 has a spraying tool 1010 mounted on the support. The spraying tool 1010 is operable to draw a liquid plant protection product, such as a pesticide, contained in a reservoir 1012 and to spray the liquid onto a plant articles in the plurality of articles 114 disposed in a path of the spray. The tool support 1004 has a robotic arm 1014 mounted on the support. In one embodiment the robotic arm 1014 may be an articulated robot such as a SCARA (Selective Compliance Articulated Robot Arm), which is simple to mount on the tool support 1004 and has a small footprint. In embodiments where the articles 114 are plant pots operations such as trimming, sticking, or other operations may be performed by the articulated robot. The apparatus 1000 also includes a plurality of cameras 1018, 1020, 1022, and 1024 mounted on respective supports 1006 and 1008, which are operable to generate images facilitating inspection of the plurality of articles 114. In other embodiments, the apparatus 1000 may only have a single tool and tool support. Alternatively, in some embodiments more than four tools may be provided.

Further examples of tools that may be mounted on one of the plurality of tool supports 1002-1008, include a labeling machine, a 3D printer head, a drilling and/or milling machine, a cutting and trimming machine, a monitoring apparatus, etc.

Actuation of the platform actuator 140 causes the platform 110 to rotate in the direction 128 to dispose successive articles in the plurality of articles 114 to be operated on by the spraying tool 1010, robotic arm 1014, and inspection cameras 1016-1022. In the embodiment shown where the base 132 is rotatable with respect to the wheeled chassis 102, the plurality of tool supports 1002-1008 would thus also move with the base. As an alternative, the platform 110 may be held in a fixed rotational orientation while the base 132 is rotated to cause the tools, 1012, 1014, and 1016-1022 to be successively disposed to perform operations on each of the plurality of articles 114. In the embodiment described above where the platform is not rotatable, the rotatable base 132 would thus provide for rotational movement to dispose each tool to operate on the articles. In the other disclosed embodiment, where the base 132 is fixed and the manipulator 122 is thus not moveable w.r.t. the wheeled chassis 102, rotational movement of the platform 110 thus disposes each of the plurality of articles 114 to be operated on by each tool.

The upper surface **112** of the platform **110** thus accommodates several articles on which operations can be performed while the apparatus **100** is moving between the pickup location **602** and the drop-off location **624**. This has the advantage over prior-art systems that need to transport articles to a fixed station where operations are performed on the plurality of articles **114** before transporting the articles to the drop-off location **624**. The relatively large upper surface **112** of the platform **110** also accommodates several articles (in this case **6** articles) for both transport to the drop-off location **624** and simultaneous performing of operations using the tools **1012**, **1014**, and **1016-1022**.

In FIG. **1**, the proximity sensor **154** of the apparatus embodiment **100** was disclosed as being implemented using a single LIDAR sensor. In the apparatus embodiment **1000** shown in FIG. **12**, the proximity sensor **154** is implemented using a LIDAR sensor **1024** and an infrared sensor **1026**, where the infrared sensor **1026** performs close range proximity detection and the LIDAR sensor performs mid-range and long-range proximity detection. Some LIDAR sensors do not provide sufficient resolution for close range objects, while new LIDAR sensors that have recently become available may provide sufficient resolution at close range. As an example, the infrared sensor **1026** may be used for detection of objects within a range of about 100 cm, while the LIDAR sensor **1024** may be used to cover ranges between about 15 cm and 6 meters.

Referring back to FIG. **1**, the apparatus **100** may further include a pair of spaced apart mounts **162** and **164** that carry the respective UWB transceivers **416** and **417** (shown in FIG. **6**). The UWB transceivers **416** and **417** are operable to receive and/or transmit radio frequency (RF) positioning signals. Ultra-wideband transceivers use a low energy level RF pulse transmission over a wide bandwidth for short-range communications and are commonly used in precision locating and tracking applications. UWB pulses have low energy and in addition to requiring less operating power, also generally do not conflict with other wireless signals. In the embodiment shown, the UWB transceivers **416** and **417** are implemented using the DWM1000 UWB wireless transceiver module manufactured by DecaWave of Dublin, Ireland, which facilitates location of objects to a precision of about 10 centimeters indoors over a range of up to about 300 meters. For the UWB transceivers **416** and **417** on the apparatus **100**, the DWM1000 module is configured as a “tag”, for which the position is to be tracked.

FIG. **13** shows a plan view of an area **1100** such as a plant nursery floor. A plurality of articles (in this case, plants in pots) are to be transported on the wheeled chassis **102** of the apparatus **100** between a pickup location **1102** and an intended drop-off location **1104** within the area **1100**. Referring to FIG. **13**, a positioning system shown generally at **1106** includes a pickup beacon **1108** positioned proximate a plurality of articles **1110** at the pickup location **1102**. The positioning system **1106** also includes a left drop-off beacon **1112** positioned proximate the intended drop-off location **1104** and a right drop-off beacon **1114** positioned proximate drop-off location **1104**. The left drop-off beacon **1112** and right drop-off beacon **1114** define a datum **1116** for indicating a desired alignment of articles at the drop-off location **1104**.

Each of the beacons **1108**, **1112**, and **1114** includes a transceiver for receiving and/or transmitting positioning signals. In one embodiment of the positioning system **1106**, the beacons **1108**, **1112**, and **1114** may also each include a DWM1000 UWB wireless transceiver module configured as an “anchor”, which provides fixed reference points for

locating the apparatus **100** within the area **1100**. The UWB transceivers **416** and **417** and the UWB transceivers on each beacon **1108**, **1112**, and **1114** each include a wireless interface, and are able to transmit and receive data signals from each other including timing information. In one embodiment communications between the UWB transceivers **416** and **417** and the UWB transceivers on each beacon **1108**, **1112**, and **1114** may be in accordance with the IEEE 802.15.4 protocol for low-rate wireless personal area networks. The UWB transceivers **416** and **417** on the apparatus **100** are in communication with the on-board controller **160** via a USB interface **412**, as shown in FIG. **6**. Advantageously, the UWB transceivers **416** and **417** and the UWB transceivers on the beacons **1108**, **1112**, and **1114** provide accurate real time positioning of the apparatus **100** within a workspace that does not rely on tracking movements of the drive wheels **104** or hub drive **150**.

The pickup beacon **1108** is used to generally indicate the pickup location **1104** where the plurality of articles **1110** are located. In this embodiment the datum **1116** provided by the left drop-off beacon **1112** and right drop-off beacon **1114** indicate a desired alignment of a plurality of articles **1122** at the drop-off location **1106**. In FIG. **13** articles in the plurality of articles **1122** that have already been unloaded have been aligned along a line **1124**, which is spaced apart from the datum **1116** by a distance **S**.

In order to determine the position of the UWB transceivers **416** and **417** it is necessary to first establish the location of each of the beacons **1108**, **1112**, and **1114** in a local coordinate frame **1126**. In one embodiment, the beacons **1108**, **1112**, and **1114** may be placed at arbitrary fixed positions and the UWB transceivers **416** and **417** and on-board controller **160** may be configured to locate each of the beacons within the local coordinate frame **1126**.

Referring to FIG. **14**, a flowchart depicting blocks of code for directing the controller **160** to locate arbitrarily positioned beacons **1108**, **1112**, and **1114** in the local coordinate frame **1126** is shown generally at **1200**. The process **1200** begins at block **1202**, which directs the controller **160** to cause the UWB transceivers **416** and **417** on the apparatus **100** to initiate transmission of positioning signals, which are received by the UWB transceivers on each beacon **1108**, **1112**, and **1114**. The UWB transceivers transmit signals over a wide bandwidth, which is equivalent to transmission of a very precise narrow pulse (about 1 nanosecond) in the time domain and facilitates accurate determination of a time of flight (TOF) for each transmitted pulse. In one embodiment the UWB transceivers may implement two-way ranging in which the transceivers exchange timing information over several transmissions between the transceivers to provide for precise TOF measurements. Signals received back at the transceivers **416** and **417** from the beacons **1108**, **1112**, and **1114** are processed to calculate distances  $d_i$  corresponding to the determined TOF for each pulse transmission. The distances between each beacon are given by:

$$d_i = TOF * c; \quad \text{Eqn 1}$$

where  $d_i$  is the calculated distance and  $c$  is the speed of light. When two-way ranging is implemented, each distance  $d_i$  is calculated based on several transmissions between transceivers, and thus provides an improved distance measurement between beacons. As described above in connection with FIG. **6**, the UWB transceivers **416** and **417** are in communication with the microprocessor **400** of the on-board controller **160** and the TOF and/or the distances  $d_i$  are thus made available to the controller **160** for further processing via the USB interface **412** to the transceivers. In some

embodiments the on-board controller **160** may receive TOF information and calculate the distances at the controller. In other embodiments received position data may already be converted into distances.

Block **1206** then directs the controller **160** to establish the local coordinate frame **1126** with respect to the beacons **1108**, **1112**, and **1114**. This involves designating one beacon as an origin of the local coordinate frame **1126** (in this case the left drop-off beacon **1112**), designating another beacon as defining a direction of the positive x-axis (in this case the right drop-off beacon **1114**), and establishing the y-axis perpendicular to the x-axis. Block **1208** then directs the controller **160** to use the calculated distances to determine the position of the remaining beacons (i.e. in this case the beacon **1108**) within the local coordinate frame **1126**. The beacons **1108**, **1112**, and **1114**, while placed in arbitrary positions thus facilitate establishment of a fixed frame of reference **1126** for the positioning system **1106**.

Referring to FIG. **15**, a flowchart depicting blocks of code for directing the on-board controller **160** of the apparatus **100** determine its position within the area **1100** is shown generally at **1300**. The process **1300** begins at block **1302**, which directs the microprocessor **400** of the on-board controller **160** to cause the UWB transceivers **416** and **417** to transmit positioning pulses, generally as described above. The transmission of the positioning pulses, when received at the beacons **1108**, **1112**, and **1114** cause transmission of return positioning pulses from the beacons including data related to the TOF associated with the pulse transmission. The process **1300** then continues at block **1304**, where the positioning pulses are received back at the UWB transceivers **416** and **417** and three distances  $d_i$  are calculated for each of the UWB transceivers based on the determined TOF as described above.

At block **1306**, the distances  $d_i$  are provided to the microprocessor **400** for further processing. Block **1308** then directs the microprocessor **400** to uniquely locate the UWB transceivers **416** and **417** in the local coordinate frame **1126** with respect to the beacons **1108**, **1112**, and **1114**. The location process generally involves finding the intersection between circles centered at each of the beacons **1108**, **1112**, and **1114** and having a respective radius of  $d_i$ . In practice, noise and other errors will likely not yield a unique intersection point, but probabilistic methods such as a least squares approximation may be used to provide a relatively precise estimate of the location of each sensor. If a more precise estimation of the location of the sensors **416** and **418** is required, an additional beacon (not shown) may be added to further reduce uncertainties associated with the position calculation. The process **1300** will generally be repeated at a repetition rate sufficient to locate the apparatus **100** in real-time or near-real time, while reducing the power consumption of the transceivers that may be powered by batteries.

The apparatus **100** may use the positional information for navigating the wheeled chassis to pick up articles from the plurality of articles **1110** at the pickup location **1104** and to move between the pickup location and the drop-off location **1106**, and to place articles in the plurality of articles proximate the destination location. The position of the apparatus **100** may be derived from the positions of the UWB transceivers **416** and **417**, for example by taking a midpoint between the positions for each of the UWB transceivers **416** and **417** or some other reference point on the wheeled chassis **102**. Additionally, the respective positions provided for the spaced apart mounts **162** and **164** provide sufficient separation between the UWB transceivers **416** and **417** to

permit determination of an orientation or heading of the apparatus **100** within the local coordinate frame **1126** for the positioning information provided by the respective transceivers.

In one embodiment, the real-time location and orientation provided by the positioning system may be used for steering the wheeled chassis along a path **1224** between the pickup location **1104** and drop-off location **1106**. Additionally, the LIDAR proximity sensor **154** may simultaneously receive proximity signals indicative of obstacles in the path of the wheeled chassis **102**. The microprocessor **400** may use the received proximity signals from the LIDAR proximity sensor **154** and the positional information provided by the positioning system to modify the path **1224** of the wheeled chassis to avoid detected obstacles.

When the wheeled chassis **102** is within a pre-determined range of the pickup location **1104**, the proximity signals received from the proximity sensor **154** may be processed by the microprocessor **400** to determine whether obstacles in the path of the wheeled chassis **102** correspond to any of the plurality of articles **1110** to be transported, and in response causing the wheeled chassis to steer towards one of the articles in the plurality of articles. In general, LIDAR and/or other proximity signals provided by the proximity sensor **154** may be used in combination with data provided by the UWB transceivers **416**, **417** on the apparatus **100** and the UWB transceivers on each beacon **1108**, **1112**, and **1114** to provide details of the environment, articles **1110** and **1122**, obstacles, and the position of the apparatus **100** within the area **1100**. Based on this information, the apparatus **100** may determine the path **1224** and make necessary adjustments to the path during movement.

Similarly, when path **1224** of the wheeled chassis **100** is within a pre-determined range of the drop-off location **1106**, the microprocessor **400** may cause the wheeled chassis **102** to steer to a first location defined with respect to the second beacon **1114** (and/or the first beacon **1112**) for unloading a first article at the **1106**. Subsequently, for additional articles in the plurality of articles **1110** the microprocessor **400** may cause the wheeled chassis to steer to successive locations (for example the location **1226**) defined with respect to the first and second beacons **1112** and **1114** for unloading of subsequent articles in the plurality of articles.

While specific embodiments have been described and illustrated, such embodiments should be considered illustrative of the invention only and not as limiting the invention as construed in accordance with the accompanying claims.

What is claimed is:

**1.** A method for transporting a plurality of articles between a pickup location and an intended drop-off location on a wheeled chassis having a pair of transceivers disposed in spaced apart relation on the wheeled chassis, the method comprising:

- positioning a pickup beacon proximate the plurality of articles at the pickup location;
- positioning a left drop-off beacon and a right drop-off beacon on either side of the intended drop-off location, the left and right drop-off beacons indicating a desired alignment of the plurality of articles at the intended drop-off location;
- receiving location signals at transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis;
- processing the location signals to determine a location and orientation of the wheeled chassis with respect to the beacons;



navigating the wheeled chassis using the determined location and orientation of the wheeled chassis to: pick up successive articles of the plurality of articles proximate the pickup location; move between the pickup location and the intended drop-off location; and place articles at the intended drop-off location in an aligned relation with respect to the left and right drop-off beacons.

**2.** The method of claim 1 wherein receiving location signals comprises:

- transmitting ultra-wideband (UWB) signals at the transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis; and
- receiving the UWB signals at the other transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis.

**3.** The method of claim 1 wherein navigating comprises: using the location signals to determine a real-time location and orientation for steering the wheeled chassis along a path between the pickup location and drop-off location; receiving proximity signals indicative of obstacles in the path of the wheeled chassis; and using the received proximity signals and location signals to modify the path of the wheeled chassis to avoid detected obstacles.

**4.** The method of claim 3 wherein receiving the proximity signals comprises generating proximity signals using at least one of an optical sensor, an infrared sensor, light detection and ranging (LIDAR) sensor, and an ultrasonic sensor.

**5.** The method of claim 3 wherein receiving the proximity signals comprises receiving:

- a first proximity signal from an infrared sensor operably configured to indicate close range obstacles; and
- a second proximity signal from a light detection and ranging (LIDAR) sensor indicating mid and far range obstacles.

**6.** The method of claim 3 further comprising, when the path of the wheeled chassis is within a pre-determined range of the pickup location, processing the received proximity signals to determine whether obstacles in the path of the wheeled chassis correspond to any of the plurality of articles to be transported, and in response causing the wheeled chassis to steer towards one of the articles in the plurality of articles.

**7.** The method of claim 3 further comprising, when path of the wheeled chassis is within a pre-determined range of the intended drop-off location, causing the wheeled chassis to steer to a first location defined with respect to one of the left drop-off beacon and the right drop-off beacon for unloading of a first article.

**8.** The method of claim 7 further comprising causing the wheeled chassis to steer to successive locations defined with respect to the one of the left drop-off beacon and the right drop-off beacon for unloading of a second article and subsequent articles in the plurality of articles.

**9.** A system for transporting a plurality of articles between a pickup location and an intended drop-off location, the system comprising:

- a wheeled chassis having a pair of transceivers disposed in spaced apart relation on the wheeled chassis;
- a pickup beacon positioned proximate the plurality of articles at the pickup location;
- a left drop-off beacon and a right drop-off beacon positioned on either side of the intended drop-off location, the left and right drop-off beacons indicating a desired alignment of the plurality of articles at the intended drop-off location, each beacon including a transceiver; and

wherein the transceivers on the beacons and the pair of transceivers on the wheeled chassis are operably configured to receive location signals and process the location signals to determine a location and orientation of the wheeled chassis with respect to the beacons for navigating the wheeled chassis to pick up articles in the plurality of articles proximate the pickup location, to move between the pickup location and the intended drop-off location, and to place articles in the plurality of articles at the intended drop-off location in aligned relation with respect to the left and right drop-off beacons.

**10.** The system of claim 9 wherein the transceivers disposed on each beacon and the pair of transceivers on the wheeled chassis comprise ultra-wideband (UWB) transceivers.

**11.** The system of claim 9 further comprising at least one proximity sensor disposed on the wheeled chassis, the proximity sensor being operable to provide an indication of obstacles in the path of the wheeled chassis.

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